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AN ADAPTIVE INSPECTION SAMPLING PROGRAM FOR DETERMINING COATING FAILURE OF NIMITZ CLASS AIRCRAFT CARRIER TANKS AND VOIDS

by

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This thesis addresses Nimitz class aircraft carrier tank and void maintenance. It contributes to the solution of current maintenance problems in four ways. First, it stratifies Nimitz class aircraft carrier tanks and voids into ten groups and assigns a criticality factor to each group. These groups and criticality factors can be extended to other classes of ships. Second, it demonstrates methods to estimate the survival function of tank and void coating lifetimes based on inspection data. Actual estimates of the survival function for each group are given, but are based on current data of questionable quality. Third, it develops a decision tool to plan inspections and budget maintenance costs over multiyear periods. Preliminary application of this tool demonstrates the cost effectiveness of driving maintenance by inspection. Finally, sampling plans provided to AIRLANT for CVN 71 1997 EDSRA and CVN 73 1997 SRA are discussed. These sampling plans were developed to obtain unbiased estimates of the current proportion of failed tanks within each group. By using plans such as these, unbiased estimates of the survival function for each group can be computed. This thesis provides a framework for developing a long term inspection and maintenance program.

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AN ADAPTIVE INSPECTION SAMPLING PROGRAM FOR DETERMINING COATING FAILURE OF NIMITZ CLASS AIRCRAFT CARRIER TANKS AND VOIDS

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

This thesis addresses Nimitz class aircraft carrier tank and void maintenance. It contributes to the solution of current maintenance problems in four ways. First, it stratifies Nimitz class aircraft carrier tanks and voids into ten groups and assigns a criticality factor to each group. These groups and criticality factors can be extended to other classes of ships. Second, it demonstrates methods to estimate the survival function of tank and void coating lifetimes based on inspection data. Actual estimates of the survival function for each group are given, but are based on current data of questionable quality. Third, it develops a decision tool to plan inspections and budget maintenance costs over multiyear periods. Preliminary application of this tool demonstrates the cost effectiveness of driving maintenance by inspection. Finally, sampling plans provided to AIRLANT for CVN 71 1997 EDSRA and CVN 73 1997 SRA are discussed. These sampling plans were developed to obtain unbiased estimates of the current proportion of failed tanks within each group. By using plans such as these, unbiased estimates of the survival function for each group can be computed. This thesis provides a framework for developing a long term inspection and maintenance program.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This thesis addresses the complex and costly issue of Nimitz class (CVN 68 and beyond) aircraft carrier tank and void maintenance. It contributes to solution of current maintenance problems in four ways.

First, it stratifies Nimitz class aircraft carrier tanks and voids into ten groups along with the assignment of a criticality factor to each group. The groups are validated by both expert opinion and data analysis (Chapter V). These groups and criticality factors can be extended to other classes of ships and have already been used for conventional powered aircraft carriers CV 63 and CV 64.

Second, it demonstrates methods to estimate the survival function of tank and void coating lifetimes based on the records found in the Tank and Void Database (T&VDB). Actual estimates of the survival function for each group are given, but are based on current data of questionable quality. Reliable estimates of the survival function can not be obtained until credible inspection and maintenance data are routinely entered into the T&VDB.

Third, it develops a decision tool to plan inspections of a tank or void in the 72 to 96 month period between overhauls. Preliminary application of this tool demonstrates the cost effectiveness of driving maintenance by inspection of tanks and voids between overhaul periods. It also provides a tool for quantifying long term costs of various maintenance options. With this tool, the maintenance managers can plan and budget tank and void maintenance costs over multiyear periods.

Finally, sampling plans provided to AIRLANT for CVN 71 1997 EDSRA and CVN 73 1997 SRA are discussed. These sampling plans were developed to obtain unbiased estimates of the current proportion of failed tanks within each group. By using plans such as these, unbiased estimates of the survival function for each group can be computed.

Several specific recommendations for immediate improvement of tank and void maintenance are:

1. Update Preventive Maintenance System Maintenance Requirements Cards to specifically require records of all tank and void inspections be entered into the T&VDB.
2. Establish a ship's tank and void coordinator as a single point of contact for the T&VDB.
3. Establish a formal path and periodicity for T&VDB updates and information transfer.
4. Generate a routine report of current and historical tank and void conditions specifically for use by maintenance managers to plan tank and void work.

This thesis provides a framework for developing a long term inspection and maintenance program. It is expected that the approaches outlined in this thesis will evolve as more is learned about the deterioration process of tank and void coatings and as new technologies for maintaining and inspecting the coatings become available.

I. INTRODUCTION

Aircraft carriers are vital national assets from which our nation projects it's will, might, and foreign policy. They are often called to action in the far corners of the earth. Their presence shows U.S. resolve in foreign policy matters and provides the military punch necessary to implement those policies. Figure I-1 shows USS GEORGE WASHINGTON (CVN 73) performing replenishment of JP-5 fuel, for its' airwing, while underway in support of operation "Joint Endeavor."

Figure I-1 USS GEORGE WASHINGTON (CVN 73) and USS ARTHUR W. RADFORD (DD 968) performing simultaneous underway replenishment of JP-5 fuel from USS MERRIMACK (AO 179) in support of operation "Joint Endeavor."

The economic realities of our nations budget have effected these ships. We are asking the current generation of aircraft carriers, the USS NIMITZ class (CVN 68 and beyond), to last fifty years, twenty years longer than was planned for their predecessors. To sustain these ships, we must ensure that they receive good and timely maintenance and that the funds allocated for that maintenance be expended in the wisest possible manner. Proper maintenance of the tanks and voids onboard these ships is a key element in ensuring their readiness through the midpoint of the next century. This thesis will address how to best schedule the inspections of tanks and voids used to drive this maintenance.

A. BACKGROUND

Aircraft carriers have been characterized as floating airports and even small cities. Beneath the action of the flight deck and the maintenance hanger lies a different characterization. Outboard of the machinery, living, and work spaces on the fourth and lower decks, and below the eighth deck lies the tank and void system. These tanks carry the fuel and other fluid resources that make the flight of aircraft possible, and that maintain the list and trim of the ship to make those operations viable. Proper maintenance of this hidden system is imperative to ensure the purity of fluid cargo, the ability of the ship to meet list and trim requirements, and the structural integrity of the ship.

Tank and void maintenance is currently one of the top ten Housekeeping and Maintenance Engineering (HM&E) costs of maintaining the US carrier fleet (Scalet 1996), with costs estimated at 24.7 million dollars per ship, per maintenance cycle (about 60 months) or approximately 12.8 percent of total HM&E expenditures in 1994 (Scalet 1995). Since tank repairs must be performed in dry-dock the performance of these repairs can become the critical path maintenance item for exiting dry-dock as was the case for the CVN 69 1995 Complex Overhaul. The danger and physical difficulty involved with tank maintenance and inspection require sound planning to minimize inspections while finding

all necessary repairs in time to plan and execute them at lowest cost and with the smallest operational impact to the ship.

In her thesis LT Cynthia Womble (Womble 1994) documented the need for an inspection plan and record system to better track and predict the failure behavior of Nimitz class aircraft carrier (CVN 68 class) tank and void coatings. This inspection plan and record system must be capable of providing the ship's maintenance manager with the necessary information to make well-informed decisions about which tanks and voids to inspect and repair at each availability. Engineers at Planning and Engineering for Repairs and Alterations for Aircraft Carriers (PERA(CV)) have developed an inspection record data-base along with an inspection form to be filled out by personnel inspecting tanks and voids (CLER 1995). This data-base is currently being installed on all CVN 68 class and several earlier class aircraft carriers.

B. THE PROBLEM

Maintenance managers have adopted several conservative schemes, based on their individual experience and priorities, with which to overhaul tanks. While the specifics vary slightly from ship to ship, the basis of each scheme is to overhaul as many tanks at each dry-docking as possible. Planning which tanks to overhaul is no small task. The majority of the tanks under consideration can only be overhauled while the ship is in dry-dock which occurs approximately every 72 to 96 months of ship life. Overhauls planned well in advance of dry-docking availability are expensive, but significantly less expensive than those found after the initial planning period. In order to know which tanks to schedule for overhaul, it is necessary to inspect them prior to the initial planning period for the dry dock overhaul. Inspections are performed by ships force and by Intermediate Maintenance Activity (IMA) inspectors in port at approximately 24 month intervals. Only partial inspection of the ship's tanks and voids can be completed each 24 month inspection opportunity. The operational requirements of maintaining minimum fluid volumes, hazards of shifting fluid cargo (especially JP-5) in port, and limited available man-hours (cleaning and inspecting takes about seven days per tank) and funds preclude 100% tank and void inspection during any period short of a Complex Overhaul (COH). To further complicate matters records of past inspections and maintenance are sparse, and of variable quality.

An inspection plan should take into consideration all of these factors and be designed to minimize total tank and void maintenance costs while maintaining safety and readiness standards. Specifically the plan needs to:

1. Minimize the total number of tanks and voids inspected at any single inspection opportunity.
2. Minimize the total number of tanks with undetected coating failures.
3. Be adaptable to individual ship needs and condition changes.
4. Incorporate the difference in tank function and the effects of tank failure into the decision process.

Development of a comprehensive inspection plan that is feasible and meets these objectives will take the combined effort of the maintenance planners, civilian maintenance workers, Carrier Engineering Maintenance Assistance Team (CEMAT), Planning and Engineering for Repairs and Alterations Aircraft Carriers (PERA(CV)) maintenance assistance personnel, ship's force personnel and supervisors, and AIRLANT / AIRPAC leadership.

This thesis contributes to the development of an inspection plan. In Chapter II current maintenance planning and data collection procedures are discussed. Chapter III provides a brief background of the principles of corrosion and direct chemical attack, the mechanism by which tank coating is destroyed. In Chapter IV, tanks and voids are stratified into groups based on engineering considerations and assigned a criticality factor. Survival functions of tank and void coating lifetimes are estimated based on available data for each group in Chapter V. These survival functions are used to check the groupings of Chapter IV. Chapter VI discusses development of a life-cycle decision model for inspection planning. In Chapter VII the sampling plans to provide those estimates for

CVN 71's 1997 EDSRA and CVN 73's 1997 SRA are discussed. Chapter VIII provides conclusions and recommendations.

II. TANK AND VOID MAINTENANCE AND INSPECTION PLANNING PROBLEMS

In FY 1994 Commander Naval Air Forces Atlantic (AIRLANT) spent 9.7 million dollars on Intermediate Maintenance Availability (IMA) level tank and void maintenance and repair for five aircraft carriers. A significant portion of this expense was in the areas of growth (expansion of a current work package to incorporate related maintenance found to be required after the work package was issued) and new-work (issuance of a new work package typically after close of the maintenance planning window for pre-planned work) (Scalet, 1995). This unplanned maintenance expense directly effects the maintenance dollars available for other projects. Unglamorous as they may be, tanks and voids were the critical path dry-dock maintenance project on the CVN 69 in her last (FY 1994) depot availability, predominantly due to growth and new-work. Of all Atlantic Fleet carrier tanks and voids which work was performed in FY 1994, 52% of the Tanks and Voids worked were opened due to Tank Level Indicator (TLI) failure (Scalet, 1995). The unsatisfactory coating conditions found during these TLI repairs precipitated a substantial portion of the new-work for tanks and voids in FY 1994. Clearly we are not doing an adequate job of tracking the status of a system, when more than 50% of the maintenance needs for that system arise out of surprise findings.

A. SHIP BOARD INSPECTION PROCEDURES

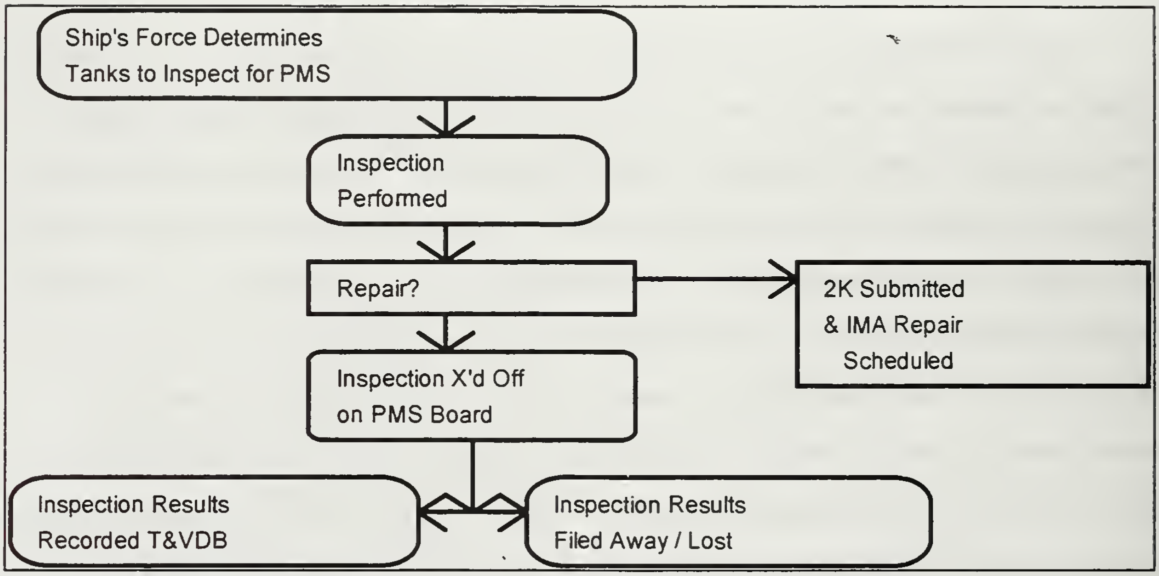

Figure II-1 Shipboard tank and void inspection process.

Tank inspections, dictated by Preventative Maintenance System (PMS) requirements, are controlled by several different work centers aboard the ship. Inspection of fuel tanks by the Fuels Division often requires access through voids that are inspected by the Damage Control division. Simultaneous inspection of both the fuel tank and the access void is rare. Thus work required to inspect the access void separately results in duplication of effort. Once tanks are inspected, the Maintenance Petty Officer (PO) provides his Work Center Supervisor (WCS) with an inspection sheet. If unsatisfactory conditions are found in the inspection, a PMS form 2190-2K (2K) is created and work is added to the ships next availability (planned work created) via the Consolidated Ship's Maintenance Plan (CSMP). Otherwise, no 2K is submitted for the inspection. There is no systematic institutionalized procedure for keeping records (other than those generating 2K's). How they are kept differs by the division and work center supervisor. For example, the CVN 69 Fuels Division maintains only the most current record in paper form and historical records are discarded. The CVN 69 Damage Control division maintains records electronically. In addition, to the records kept by each division, each carrier has a Tank and Void data base (T&VDB), designed by PERA(CV) engineers, whose purpose is to keep records from all tank and void inspections in electronic form. The T&VDB is kept on a dedicated PC in one location aboard ship and requires additional effort to enter inspection data.

Periodically, (such as at the end of every availability) the ship's T&VDB is downloaded to PERA(CV)'s T&VDB which contains tank and void maintenance and inspection records for all carriers including records for work done in the shipyards. In the past, results of inspections were not usually recorded in the T&VDB. PERA(CV) is trying to reconcile this. Figure II-1 documents the ship's tank and void inspection process.

B. FLAWS IN THE MAINTENANCE PLANNING PROCESS

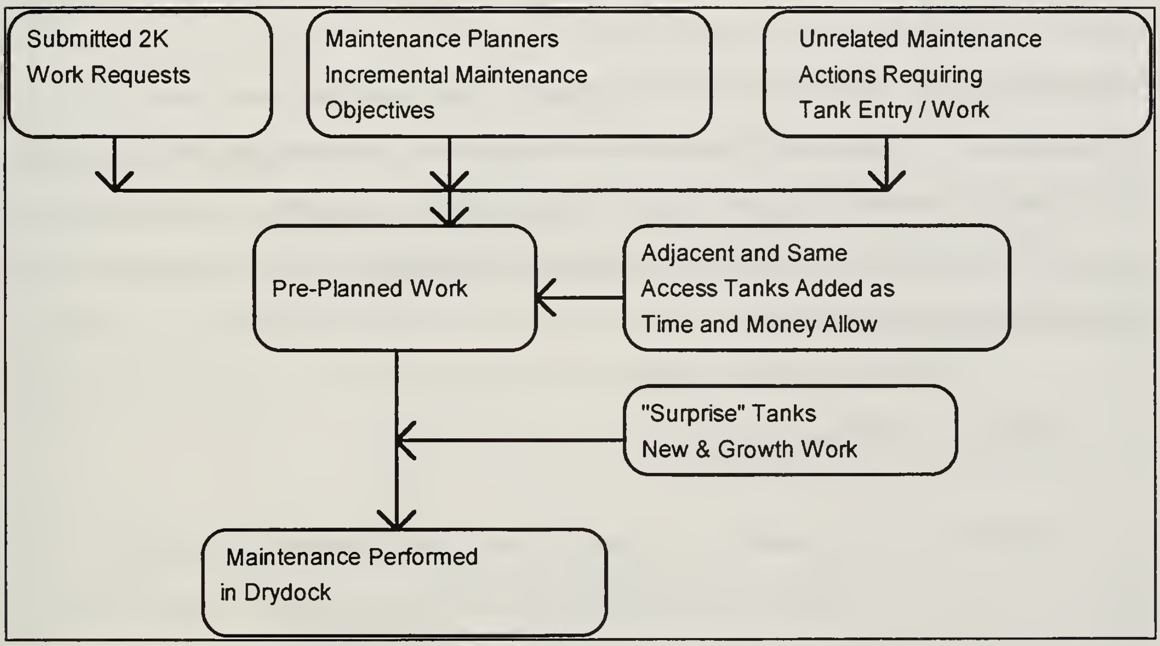

Figure II-2 Current maintenance planning process.

Currently, no information (other than repair 2K's) is systematically cycled back to the maintenance managers to plan future work. This is shown in Figure II-2. In particular, record is often not kept or made available to the maintenance planning manager about the tanks that have been inspected but require no further work by either the ships force or IMA inspectors. This leads to frequent inspection of some tanks and voids and infrequent or no inspection of others. Thus, it is difficult for a maintenance planning manager to get an unbiased overall picture of the current conditions of tanks and voids. Information about tanks and voids that have exhibited some deterioration but not enough to generate a 2K work request is also lost. This information, if recorded and analyzed, could provide valuable insight into the process of coating failure. Coating deterioration rates have never been quantified for tanks and voids in an operational setting. Additionally, tanks and voids that exhibit some deterioration are prime candidates for future planned work. Knowledge of their deteriorating condition could provide savings in inspections and repair expense.

Maintenance planning managers do not have the information and tools they need to plan tank and void overhauls. This results in work being performed as more costly new or growth work rather than pre-planned work. In addition, when new or growth work is discovered ships are often forced to perform sensitive and hazardous operations such as transferring fuel. Pre-planning gives the ship an opportunity to prepare for tank and void maintenance prior to entering port. Better record keeping can provide the information necessary to develop better and more precise analytic tools with which the amount of unplanned maintenance is reduced.

C. TANK & VOID DATA BASE

PERA(CV) in cooperation with American Systems Engineering Corporation (AMSEC / SAIC) and Applied Technical Systems (ATS) has developed a Tank & Void database (T&VDB). The purpose of this database is to provide the ship and maintenance managers with a method of communicating information about tank maintenance and inspections. This program is under rapid development and has gone from a single PC DOS program to a WINDOWS version suitable for installation on the ship's Local Area Network (LAN). This program provides easy data input and ready reference of tank conditions from previously entered data. In conjunction with the database, the Tank and

Void Inspection Manual, has been developed as a guide for performing inspections and recording their results. This provides consistent inspection records from both the ship's force (SF) and IMA inspectors. The inspection manual classifies the coating condition of a tanks surface as a condition value of 1, 2, 3, or 4. An example of these is shown in Figure II-3. Conditions 3 or 4 require work be performed.

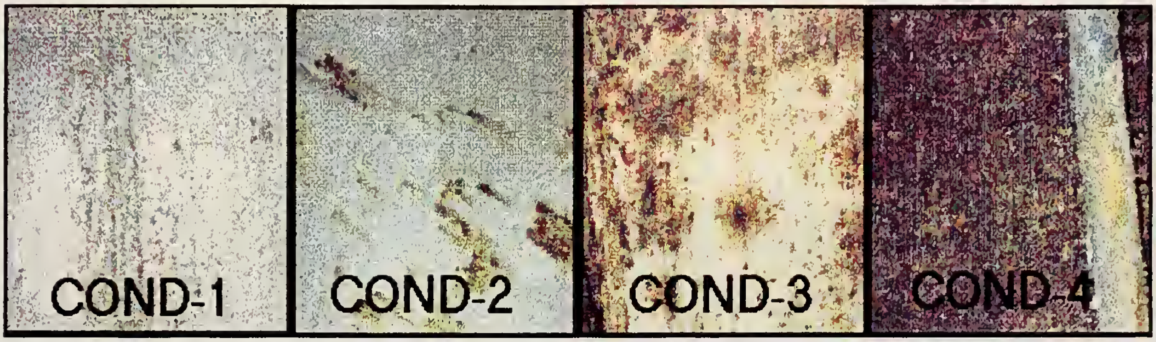

Figure II-3 Tank coating conditions (CLER, 1995).

This program has met some resistance in the fleet primarily because it requires the additional, short term, work of entering the inspection data into the computer. Updated PMS Maintenance Requirements Cards (MRC's) requiring this step be performed have yet to be issued. The gain from using the T&VDB lies in the ability to track long term processes, such as the deterioration of tank coatings, and so that maintenance planners and ships force supervisors have the necessary information to plan maintenance.

III. COATING FAILURE

The tanks and voids of concern in this thesis are all fabricated by abutment of bulkheads to the structural framing of the ship. They are constructed of the same mild and structural steel as the rest of the structural members of the ship. As such, the surfaces of these tanks must be coated to protect their structural integrity.

Figure III-1 A Shipyard worker preparing a section of tank for initial paint coating prior to its being fitted into place during new construction.

A tank or void "fails" when the coating is sufficiently corroded. Thus, tank failure or lifetime actually refers to coating failure or lifetime By keeping track of the surface

coating condition and overhauling that surface before significant opportunity for corrosion of the structural components has occurred the mechanical integrity of these components can be maintained throughout the ship's lifetime..

A. CORROSION AND DIRECT CHEMICAL ATTACK

The primary purpose of tank coatings is to protect the structural elements (made mostly of mild steel) from corrosion due to direct chemical attack by the environment to which they are exposed. It then follows that the protective coating applied to these structural members will also be subjected to direct chemical attack from the same environment. Trade-off occurs when the coating materials are more inert than the material they are protecting and are easily renewable compared to replacement of the base material. The model for this type of chemical attack was developed by Przemieniecki (Przemieniecki 1988). This model represents the rate of corrosion penetration of a specific material subjected to a direct chemical attack in a specified environment. The corrosion penetration rate is given by

$$\mu_c = \frac{(543) * w_L}{d * T * \alpha_s} \quad ,$$

where:

μ_c = rate of corrosion penetration in mils/year,

w_L = weight loss of the exposed material in mg,

d = density of the exposed material in gm/cm^3,

T = exposure time in hours,

α_S = exposed surface area in inches^2.

This model explains why different functional characterizations exist for tanks containing the same type of fluid (their exposure time and exposed surface area are dissimilar), and why tanks containing different types of fluid (the chemical attack of two different solvents causes oxidation of the protective layer to occur at different rates) are characterized separately. The type, location, and nature of the chemical attack and the properties of the

material under attack are the key factors in the deterioration of the coating material. The grouping of tanks and voids, to be discussed in Chapter IV, accounts for these and other factors.

IV. TANK AND VOID CHARACTERIZATION

The approximately 1000 tanks and voids on a NIMITZ class carrier have a wide variety of functions and failure modes. When considered in fine detail, each tank or void possesses attributes that make it unique. The eighth deck overhead views of tanks of CV 64 in Figures IV-2 and IV-3 demonstrate the arrangement of the tanks pictured in Figure IV-1. From these figures and a cross section view given in Figure IV-4, the vast differences in size, shape and location of tanks and voids is apparent.

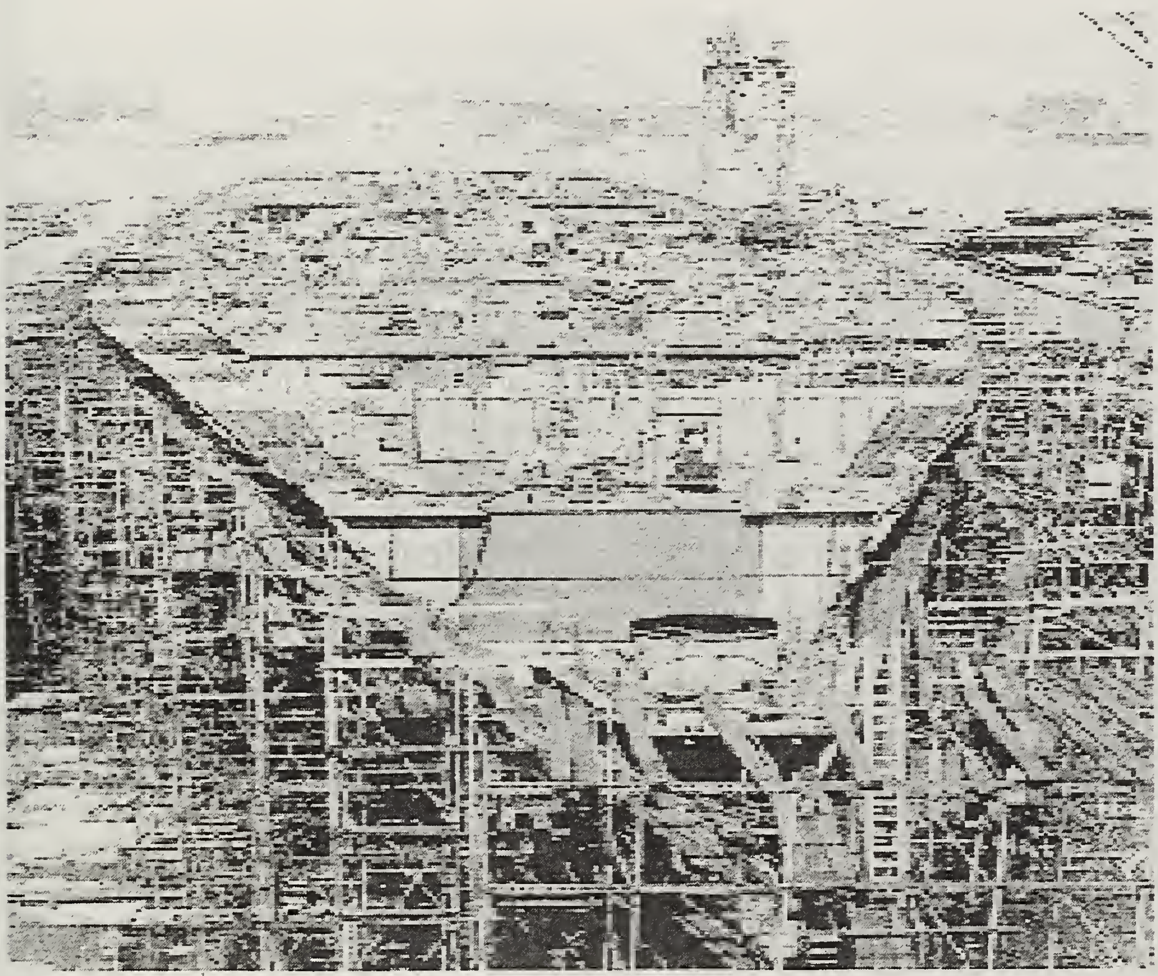

Figure IV-1 8th deck tank construction of USS KITTY HAWK CV 63.

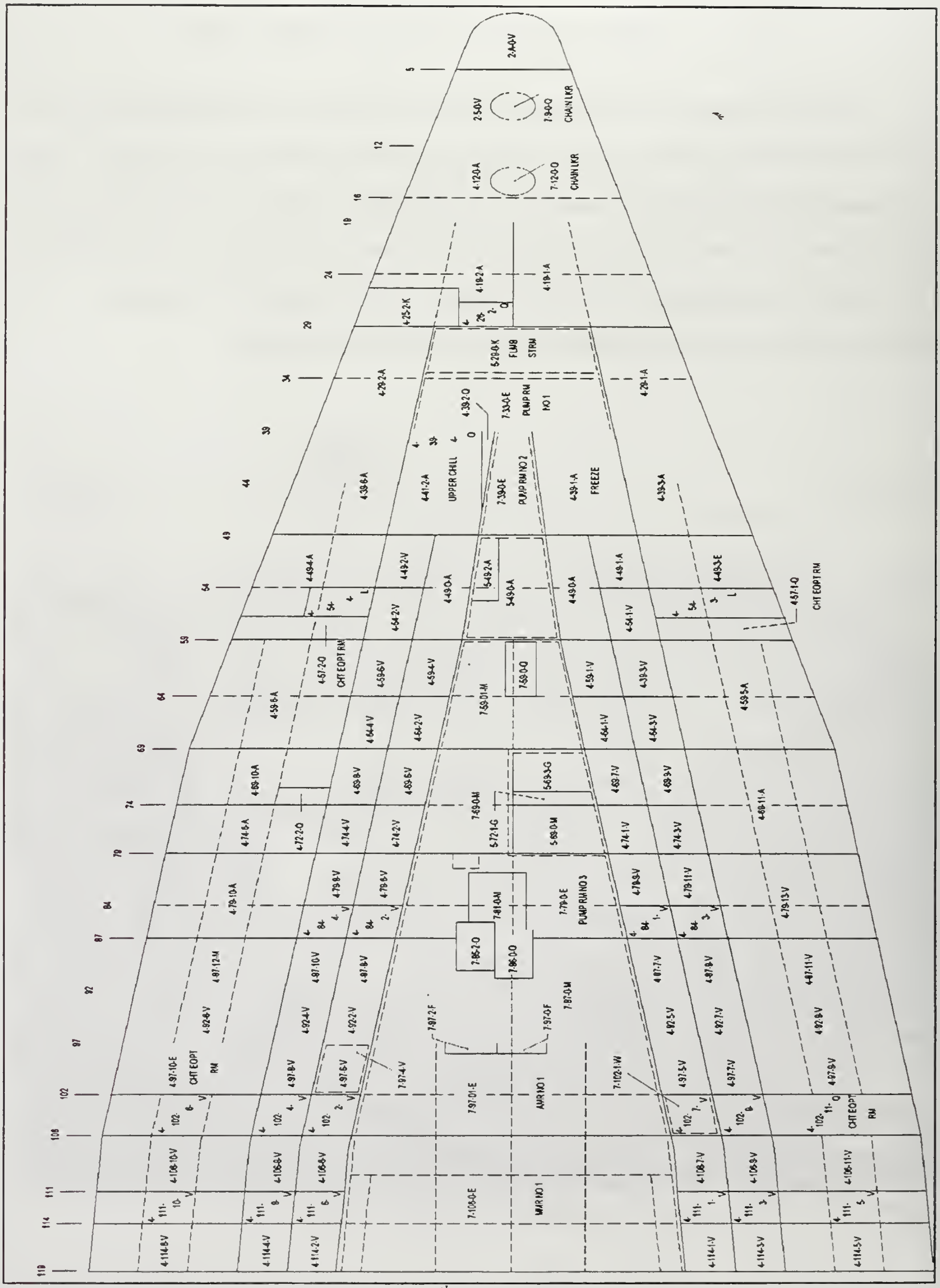

Figure IV-2Forward overhead layout of 8th deck tanks of CV 64.

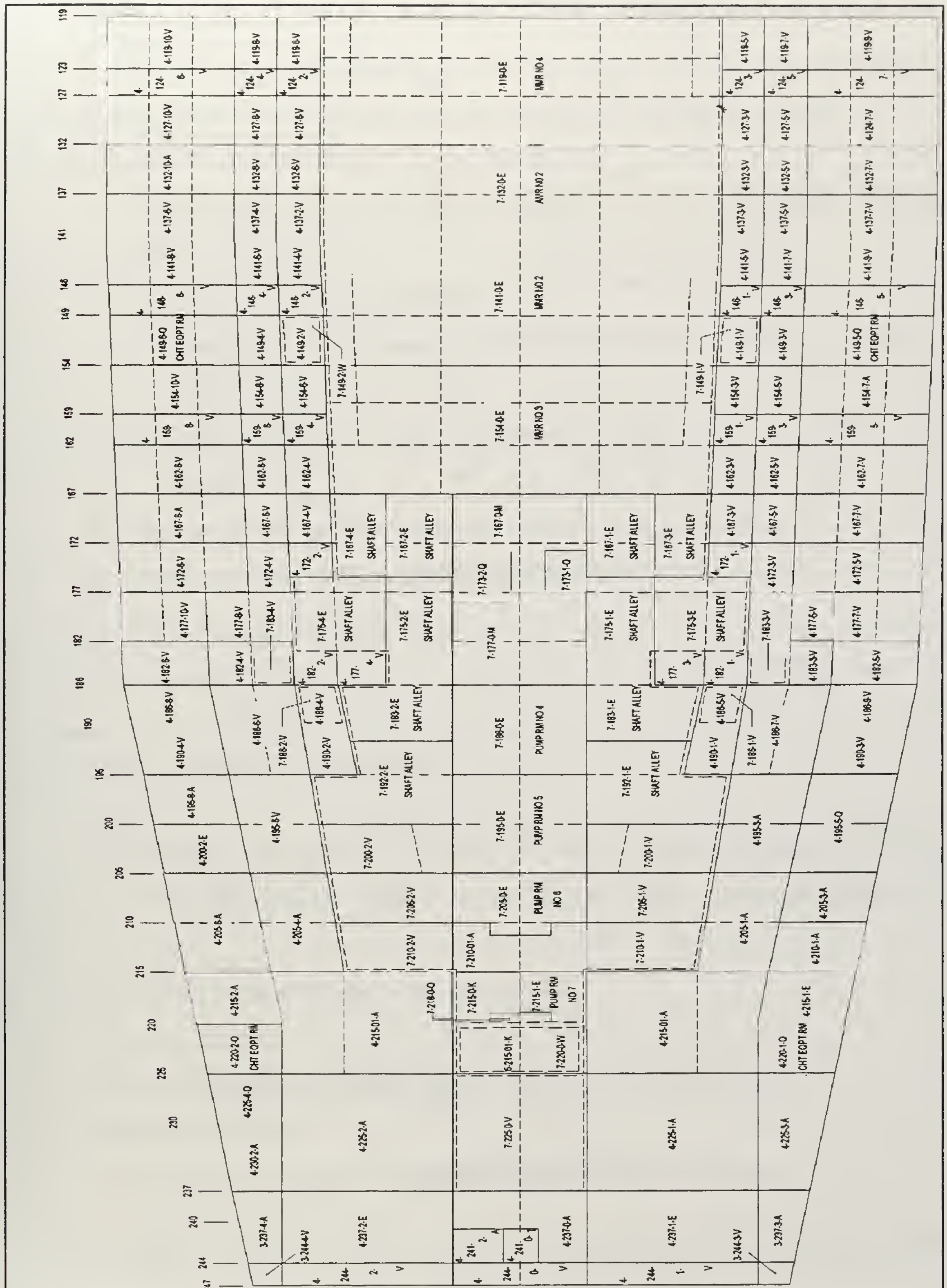

Figure IV-3 Aft overhead layout of 8th deck tanks of CV 64.

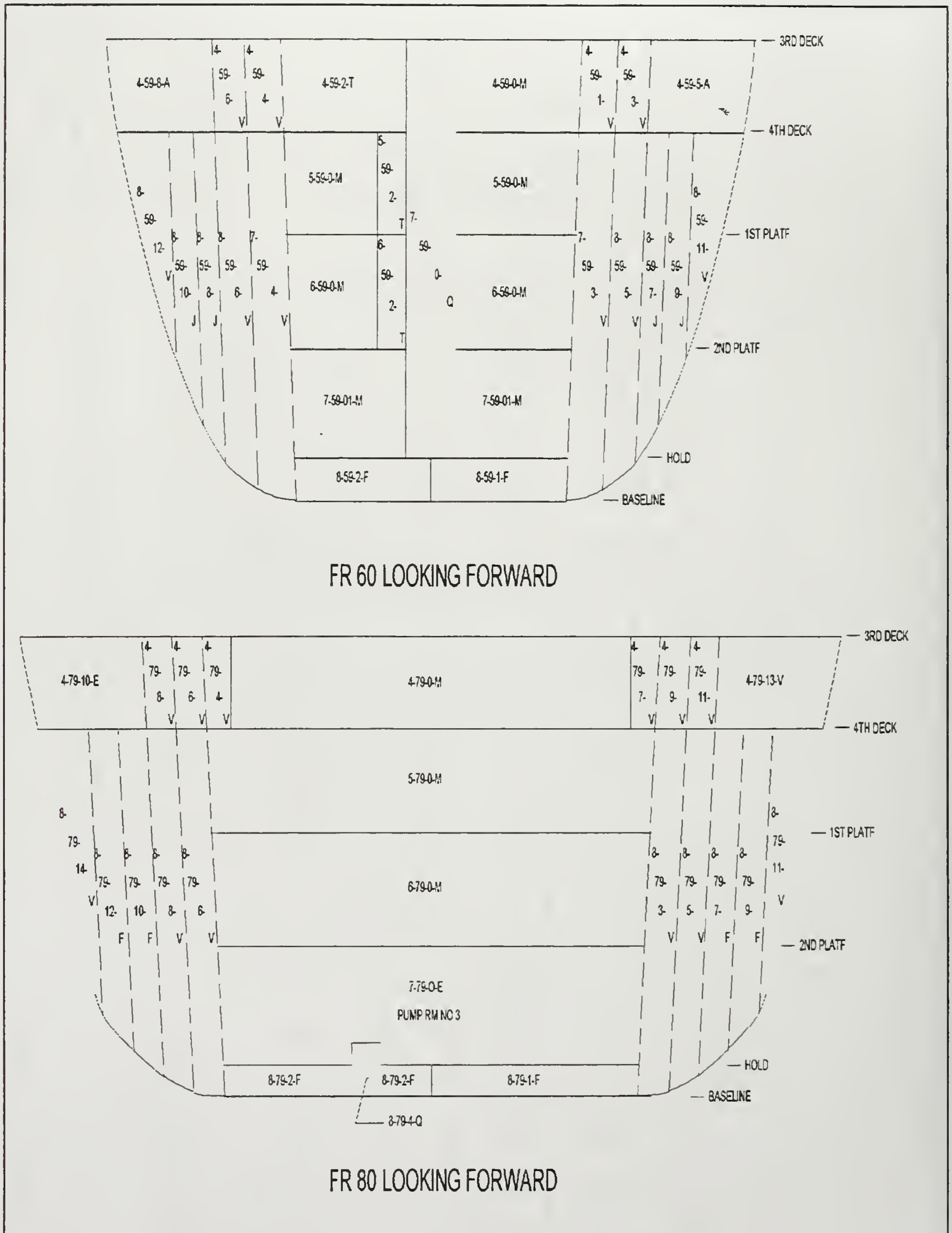

Figure IV-4 Forward looking layout of 4th and 8th deck tanks frames 60 and 80 of CV 64.

Careful aggregation of similar tanks and voids into a small number of groups of like tanks and voids can greatly simplify the planning and execution of their maintenance. In this chapter 855 of these tanks and voids are divided into ten distinct groups. Information used to develop these groups is of two types:

1. Documentation of ship configuration and tank and void designation / utilization from:
    a. Current T&VDB record entries.
    b. AutoCAD tank-top drawings of CVN's 68 through 73 fourth and eighth decks in the T&VDB.
    c. Ship's configuration plate drawings on file at PERA(CV) for CVN's 68 through 73.
2. Personal interviews with Engineers, Project Managers, Officers, Chiefs, and Petty Officers of the ships CVN 68, CVN 69, CVN 70, CVN 71, and CVN 72.

A. TANK CHARACTERIZATION

The chemical attack model described in the previous Chapter helps define the two major factors that are considered when grouping tanks and voids: function and failure mode.

1. The functional characterization of the tank or void.
    a. Type of liquid held.
    b. Type of function performed by the tank.
    c. Location of the tank.
    d. Coating material properties (type and composition of paint applied).
2. Major types of tank and void failure.
    a. Corrosion (coating, cathodic protection, structural, piping, and ladder failure).
    b. Contamination of contained liquid.

c. Instrumentation (tank level indicator or sounding tube failure).

When characterized according to these factors, sixteen groups of tanks are defined. Four of these groups, (Contaminated Holding Tanks (CHT), Fresh Water (FW), Chain, and Propulsion plant tanks), are not considered because they are currently maintained according to more restrictive PMS requirements. The remaining groups are aggregated into groups of similar functional and failure mode characterization. This results in the ten groups:

1. **JP-SERV** Tanks which hold purified JP-5 fuel for immediate fueling of aircraft.
2. **J (TRANS)** Tanks which are directly involved in the purification of fuel both into and (in the case of de-fueling) out of aircraft.
3. **J (FULL)** Bulk stowage tanks for JP-5 fuel.
4. **LUBE-OIL** Bulk stowage of ship's lube oil reserves and lube oil purification process tanks.
5. **SEA WTR (FREQ)** Tanks routinely exposed to sea water by design such as list control tanks.
6. **SEA WTR (INF)** Tanks that are floodable but are not by design routinely exposed to sea water such as damage control tanks.
7. **CAT WING VOIDS** The tanks that function to provide drainage for the flight deck catapult track.
8. **CAT EXHAUST** Tanks that receive the effluent from the catapult water brakes.
9. **DRY** Tanks and voids that are not flooded by design.
10. **SPONSON** Dry tanks that are created by fairing of ships hull shape.

Figure IV-5 shows the distribution of tanks and voids in these groups for CVN 73.

TANK CHARACTERIZATION: (CVN-73)	
CHARACTERIZATION GROUP:	**QUANTITY:**
JP-SERV {JP-Serv(29), Aux JP-Serv(2)}	31
J (TRANS) {COST(5), JP-Def(2), JP-Pur drn smp(2)}	9
J (FULL) {JP(51), JB(53), JOB(31), JP NSFO(14), JB NSFO(5), JOB NSFO(5)}	159
LUBE-OIL {LOSto(28), AUX LOSto(4), LOSet(17), Sump(1), Cat cyl LO Sto(1)}	51
SEA WTR (FREQ) {LC(9), Peak SWB(2), Overflow(2), Overflow Box(10), Oily Wst(11)}	34
SEA WTR (INF) {DC(69)}	69
CAT WING VOIDS {Cat Wing VoidS(232)}	232
CAT EXHAUST {CatVoid(3)}	3
DRY {CD(32), V(232)}	264
SPONSON {SponV(3)}	3
TOTAL:	855

Figure IV-5 CVN 73 tank groupings.

B. CRITICALITY OF TANKS

The severity of impact on ships mission by failure of one type of tank may differ significantly from like failure of another type of tank. To provide a means for weighing the severity of an individual failure the following evaluation priorities are established:

Ship's Mobility. Failure of a tank that effects ships mobility impacts the ships ability to travel to its assigned operating waters and its ability to conduct flight operations when in those waters.

Ship's Mission to support Air operations. Failure of a tank that effects the ships ability to conduct full flight operations directly degrades the ship's primary mission capabilities.

Ship's Structural Integrity. The honeycomb of tanks that comprise the bulk of the ship's volume below the eighth deck is created by segregation of areas between structural frames by the addition of bulkheads. While strengthening the hull, these bulkheads prevent casual observation of the condition of the ships structural members in their most critical region. Unchecked corrosion in these areas can lead directly to weakening of the ships structural integrity.

C. CRITICALITY FACTORS

Ranking the impact of a tank failure in each characterization group results in five levels of criticality. These levels are ranked values (ordinal not continuous). While it is apparent that a criticality factor four failure has a more significant impact on ships operations than a criticality factor two failure, it is not true that the significance of a failure of a tank in a group having criticality factor four will have exactly double the impact on the ship as like failure of a tank from a group having a criticality factor of two.

Affects Ship Mobility (5) Propulsion critical tanks. Used for non-nuclear CV's, the nuclear propulsion system tanks of the CVN's are under tighter (NAVSEA-08) controls thus not included.

Affects Aircraft Operations (4) Failure of these tanks impacts ship's ability to conduct full flight operations. Groupings include JP-Service tanks, which handle JP-5 directly before its use by airplanes, and Catapult Exhaust Voids that are critical for catapult operations.

Affects Ship's Structure (3) Failure of any tank affects ship's structure. The most vulnerable are assumed to have constant or regular exposure to sea water. Included in this group are Overflow Box, and List Control tanks.

Affects Cargo Use and Quality (2) Failure first occurs when the tank begins to make its cargo unsuitable for its intended purpose. Tanks such as JP stowage tanks may fail in this manner long before their level of deterioration begins to affect ship's structural integrity. Fresh Water tanks fail similarly but their controls are administered under industrial health requirements and thus (like nuclear propulsion tanks) are not included in this inspection plan.

Non Critical Failure (1) Failure of a tank having no direct adverse affect on ship's mission or operations. Tanks in this grouping include voids that are not capable of intentional sea water ballasting and lube oil bulk storage tanks.

D. DISCUSSION

The characterization of tanks and voids into the ten groups of Figure IV-5 has been briefed to representatives of AIRPAC, AIRLANT, shipboard components of CVN 69, CVN 70, and CVN 71 and twice at Tank and Void Improvement Program meetings.

This characterization is developed specifically for Nimitz class aircraft carriers which use nuclear propulsion. However, with the inclusion of two more groups Fuel Oil Storage, and Fuel Oil Service tanks, these groupings can be applied to other conventional powered aircraft carriers. These groups are analogous to JP (FULL) and JP-SERV respectively in support of the ship's propulsion plant. Fuel Oil Storage tanks are assigned criticality level three and Fuel Oil Service tanks are assigned criticality level 5. In a problem unrelated to this thesis, this characterization of tanks and voids was used to help recommend tanks to inspect for the comparison of CV 63 and CV 64. The purpose of the comparison was to assess material condition to help determine which ship to homeport in Japan where maintenance costs are appreciably higher.

V. DATA ANALYSIS

As documented by Womble (1994), the lack of tank and void inspection data is astounding. Since then, some carriers have taken proactive measures to make their tank and void inspection data available. At this time the T&VDB is being installed on all CVN 68 class ships. Still, there exists a significant gulf between the amount and quality of data available and that needed for inference and modeling. A degree of healthy skepticism must be maintained when inferring results from the data used for this analysis. Much of this data is suspect. It is not known what mechanism led to the choice of tanks that were opened or overhauled. In addition, for much of the data, the tank condition is not recorded, but inferred from maintenance performed on the tank. The real value of this analysis is to establish a methodology for further analysis as more data becomes available.

A. THE DATA

Data analyzed herein comes from the historical files of the CVN 69, 71, & 72. Two of these ships CVN 71 & 72 (commissioned in October 1986 and December 1989 respectively) are very young and have experienced few tank and void coating failures. CVN 69 (commissioned in October 1977) just completed her second dry-docking availability (FY 1986 Complex Overhaul (COH), and FY 1995 COH) and has an extensive history of repairs and inspections performed from each availability. Data from the CVN 69's 1986 COH dry-docking is however constructed from repair records several years after the fact. Appendix C, D, and E summarize the current inspection data for CVN 69, 71, and 72 respectively; Appendix F through N contain the details of each inspection period's finding for each characterization group.

Because all of the CVN 69 records from it's first COH only indicate whether a tank or void was overhauled and not it's condition prior to overhaul, actual numbers of tank and void failures are probably inflated. This conjecture is supported by the opinion of several maintenance managers, and the fact that shipyards will perform contracted

overhauls regardless of the tank condition found upon opening. This conjecture is also supported by the data. In Figure V-1, it can be seen that the percentage of JP-SERV tanks that have failed by 106 months for CVN 69 is 30% where as none were found failed by 110 months on CVN 71. Thus, inference drawn from this data will be conservative in the sense that tanks and voids will tend to have longer lifetimes than indicated by the data.

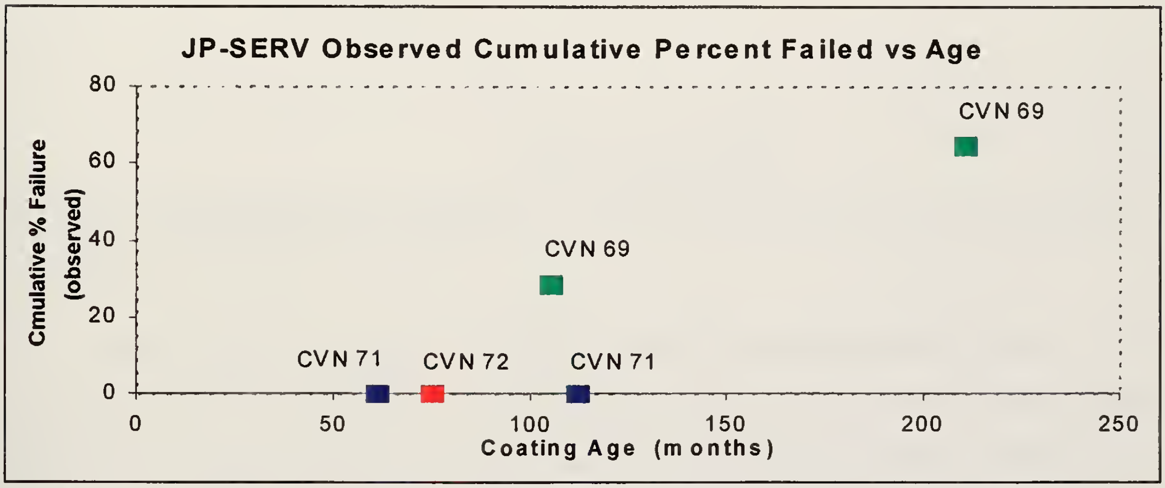

Figure V-1 Comparison of observed failures of JP-Service tank coating at different coating ages for CVN 69, 71, and 72.

The mechanism used to choose tanks for inspection can also lead to biased estimates of tank failure rates. An example of this is observed in the high failure rate and large proportion of tanks inspected in the SEA WTR (INF) group of CVN 72, shown in Figure V-2. The number inspected in this group is significantly higher than would otherwise be expected from a simple survey. Anecdotal information reveals that several ships of this class have experienced leakage in the sea water flooding valves for these tanks. A correlation of this sort appears evident in the CVN 71 110 month inspection in which almost all SEA WTR (INF) tanks inspected were found to be failed. On the CVN 72, tanks of this group that had evidence of valve leakage were preferentially inspected and many were found to be failed. Thus, the percentage of inspected tanks in this group is higher than expected for a simple random sample and the proportion of failed tanks observed is higher than can be expected in the SEA WTR (INF) group as a whole.

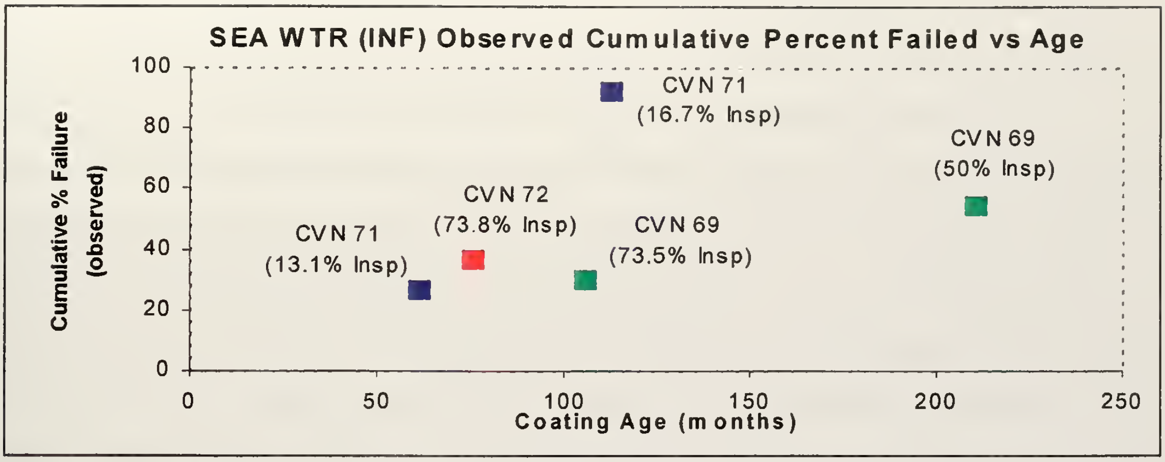

Figure V-2 Comparison of observed failures of SEA WTR (INF) tank coating at different coating ages for CVN 69, 71, and 72.

Finally, because the quality of the data is suspect and much of the detailed observations about the condition of coating failure is missing, tank and void conditions are summarized as failed (maintenance is performed when the maximum coating condition of various surfaces is 3 or 4) or as good (the maximum coating condition is 1 or 2). This is consistent with the definition of a failed tank used by maintenance managers (CLER 1995).

B. ESTIMATING TANK AND VOID SURVIVAL FUNCTIONS

Let X, with cumulative distribution function (cdf) $F(t) = P(X \leq t)$, represent the time until coating failure of a tank or void within a characterization group. The failure distribution or equivalently the survival function $S(t) = 1 - F(t)$ for tank and void coating lifetimes has never been estimated in an operational environment. Maintenance and inspection plans cannot be developed without estimates of the survival function for each of the tank and void characterization groups.

The direct chemical attack failure mechanism is a wear-out process which intuitively leads to the belief that a newer tank is less likely to fail than an older one. Parametric families of distributions most often used to model such failure mechanisms are

the one and two parameter Exponential, Weibull, Normal, LogNormal, and Gamma distributions (Tobias and Trindale 1986). The Exponential distribution models lifetimes with the memoryless property e.g., a tank that has not failed by 96 months is as likely to survive say 24 more months as a new tank is. Since the Exponential distribution is a special case of both the Weibull and Gamma distributions these two families also contain distributions with the memoryless property. In addition, the Weibull, Gamma, Normal, and LogNormal include distributions with increasing failure rate, i.e., distributions that model the intuitive notion of wear. To get estimates of S(t), these parametric distributions are fit to the data. The advantage of the parametric fit is that data in the early part of the tanks life can be used to fit the entire survival function, including the right tail of the survival function where no data has been observed.

1. Interval Censoring

The actual date of coating failure of any one tank is unknown. Tank inspection opportunities occur predominantly during in-port maintenance periods that occur approximately every 24 months. Not all tanks and voids are inspected at every opportunity. The best information about the date of coating failure is that it occurred between inspections. This leads to three types of censored failure times.

a. Right censored failure. Tanks whose coating has not failed at the time of the most recent inspection.

b. Left censored failure. Tanks which have had exactly one inspection with a coating failure at that inspection (coating failure found on first post-overhaul inspection).

c. Interval censored failure. Tanks where coating failure occurred after at least one good inspection but before a subsequent inspection.

2. Methodology

Parametric fits for the survival function S(t) are based on interval censored data and are performed by an iterative process known as the EM algorithm (Miller 1982). Software that can properly estimate survival functions based on right, left, and interval censored data are not readily available. Each iteration of the EM algorithm involves two steps: the E-step or Expectation step and the M-step or Maximization step. The $i^{th}+1$ iteration of the E-step computes the conditional expected values of the censored observations (conditioned on the data) using the parametric values from the i^{th} step. The M-step then uses these expected values as if they were the true observed values and performs maximum likelihood estimation based on complete data. Note that for the Weibull and Gamma distributions there is no closed form solution for maximum likelihood estimates thus the Newton Raphson method of finding the maxima for each step is used. This gives the $i^{th}+1$ iteration values for the point estimates of the parameters. The process is repeated until the likelihood or parameters converge, depending upon the application, (Tobias and Trindale 1986).

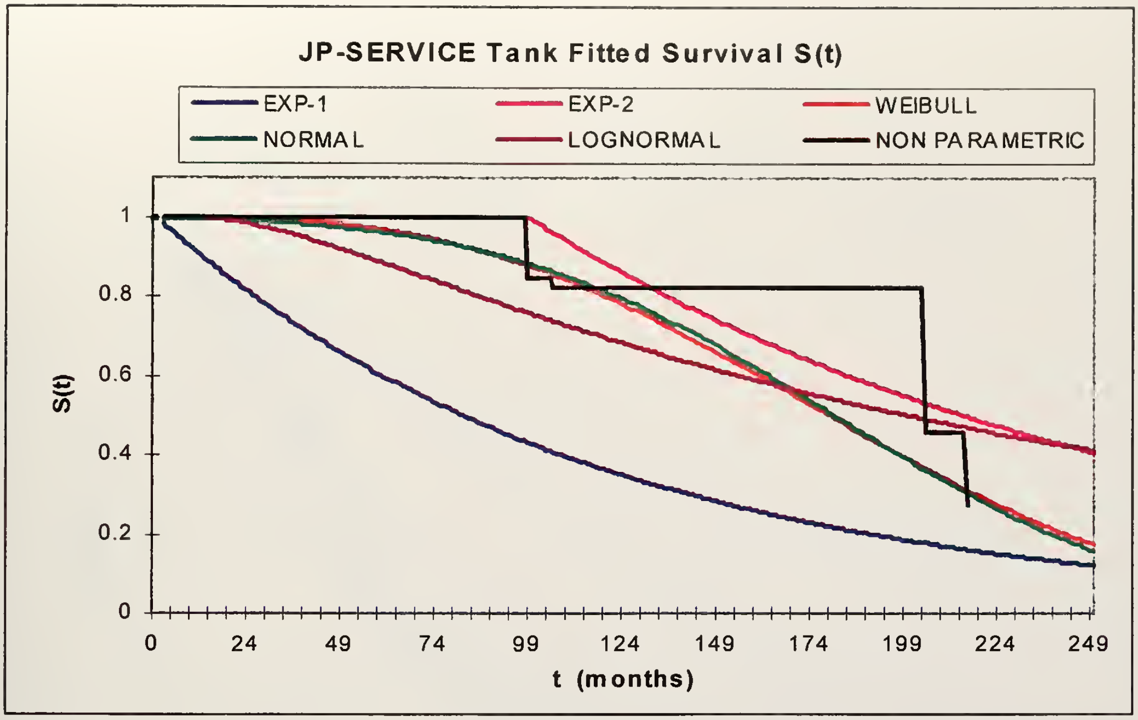

Figure V-3 Fitted parametric survival functions of lifetimes for JP-SERVICE tanks.

The Weibull distribution appears to most closely fit the data. Figure V-3 compares the fitted survival functions for various parametric distributions with the nonparametric fit. Note that in the regions of age where the inspections occur, predominantly 90-110 months and 205-220 months, the Weibull and nonparametric fitted survival functions are close to each other. For all groups the Weibull distribution is chosen to model the distribution of time until failure. Figure V-4 shows the fitted Weibull survival functions for each group.

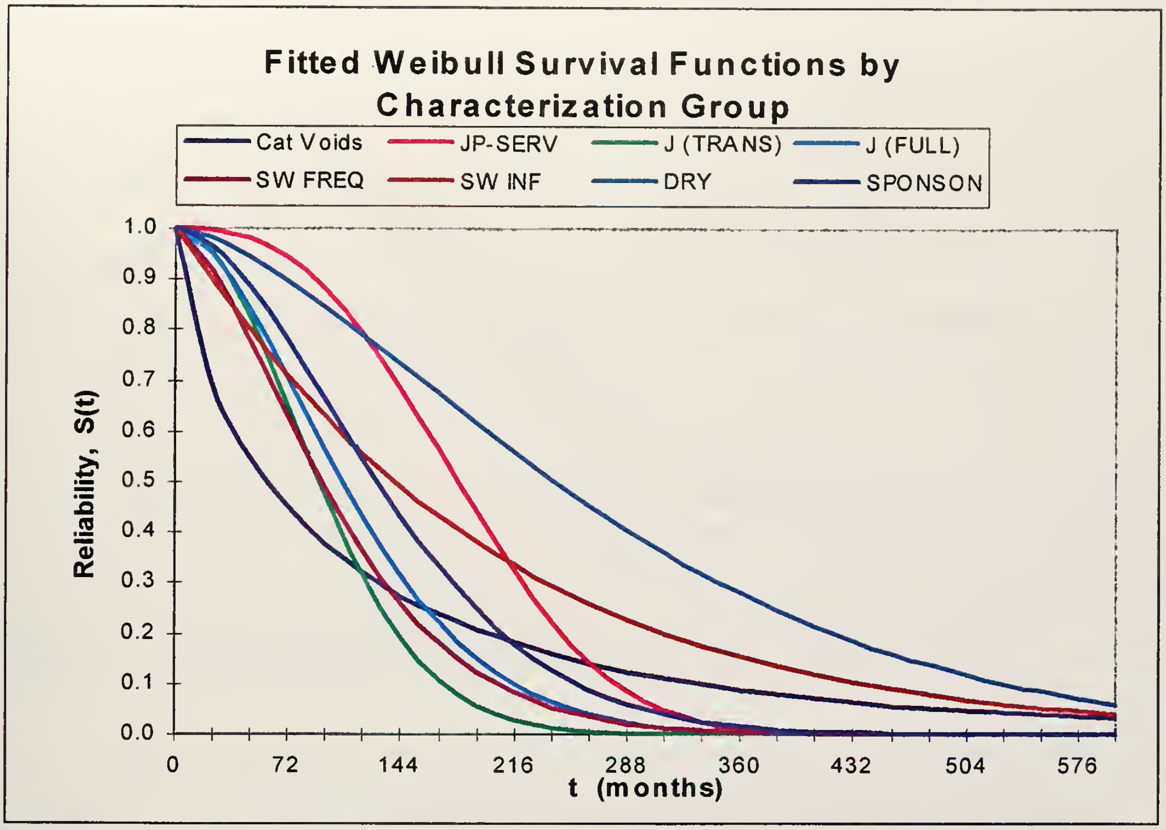

Figure V-4 Fitted Weibull survival functions for each tank characterization group.

Approximate confidence intervals (CI) for the parameters of the Weibull distribution are found by bootstrapping (Rice 1995). First, for each group a random sample (of size equal to the number of observations in that group) is generated from the fitted Weibull. Each observation in the generated sample is subjected to censoring to capture the increased uncertainty in the parametric estimates caused by interval censoring. Because the censoring mechanism for the original data is unknown, the type of censoring is determined by each observation in the original sample. For example, the first observation in the JP-SERV group is right censored into the interval $[61,\infty)$. Thus, the corresponding bootstrapped observation is taken to be censored into the interval $[61,\infty)$ if it is greater than 61 and left censored into the interval $[0,61)$ otherwise.

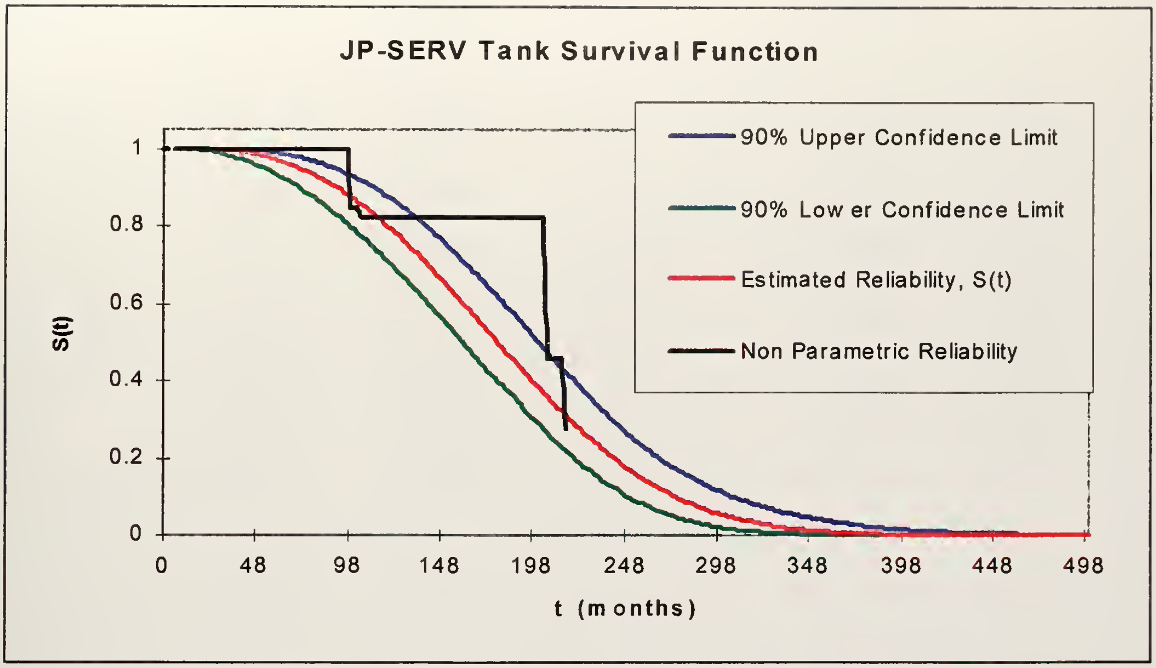

Figure V-5 JP-SERV Weibull Fit 90% Confidence Interval Bounds.

Figure V-5 illustrates the 90% confidence interval based on the Weibull fit to the JP-SERV group. Note that the Weibull fit tends to be more conservative than the non-parametric fit. It also gives estimates of the right tail of the distribution (time greater than 216 months) where no data has been collected.

3. Estimated Parameters

The analyses discussed in the previous section is repeated for each group of tanks and voids. Table I shows the estimated Weibull parameters $\hat{\alpha}$ and $\hat{\beta}$ where the Weibull survival function is given by:

$$S(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad , \quad for \quad t \geq 0 .$$

Note that there are no observed failures of LUBE OIL tanks and no observations of any kind for the CAT WING voids in the data set, hence no estimates of the survival function are made for these groups.

Group	Shape ($\hat{\alpha}$)	Std Error	Scale ($\hat{\beta}$)	Std Error
JP-SERV	2.7101	0.027	206.6	0.982
J (TRANS)	1.9631	0.033	111.8	1.074
J (FULL)	1.7264	0.007	132.9	0.455
SW FREQ	1.5314	0.016	119.0	1.084
SW INF	1.0553	0.006	198.9	1.517
DRY	1.5382	0.007	307.9	1.268
SPONSON	1.7613	0.054	159.1	2.927
LUBE OIL	-	-	-	-
CAT EXH	0.6939	0.027	99.94	5.474
CAT WING	-	-	-	-

Table V-1 Estimated parameters for the Weibull distribution for each tank and void characterization group.

Pointwise 95% confidence intervals for S(t) are computed from the confidence ellipses for α and β and are shown in Appendices D through M. The confidence intervals for α indicate α > 1 for all groups except CAT EXHAUST. For the Weibull distribution, α > 1 corresponds to a distribution with increasing failure rate (α = 1 corresponds to a constant failure rate and α < 1 corresponds to decreasing failure rate distributions). Plausible explanations for the results of CAT EXH are chance (the sample size is 8 data points) or that the CAT EXH group consists of a mixture of tanks that have different distributions (each with increasing failure rate). Such a mixture can produce an overall decreasing failure rate (Barlow and Proschan 1963).

C. ANALYSIS OF TANK AND VOID GROUPINGS

Data from CVN's 69, 71, & 72 are used to check the choice of the ten characterization groups. Figure V-6 shows the bootstrapped estimates of the α and β parameters for all ten groups. Note that each group forms an elliptical region and that many of the groups are clearly separated. This supports the original choice of tank and void groups characterized by function and failure mode.

To see whether characterization groups can be further divided this analysis is repeated for subgroups within characterization groups. Within each characterization group, bootstrapped estimates of α and β from subgroups are compared to each other and the aggregate bootstrapped estimates for the entire group. All subgroups within each major characterization show substantial overlap indicating that, at the current level of data resolution, the characterization groups can not be divided further.

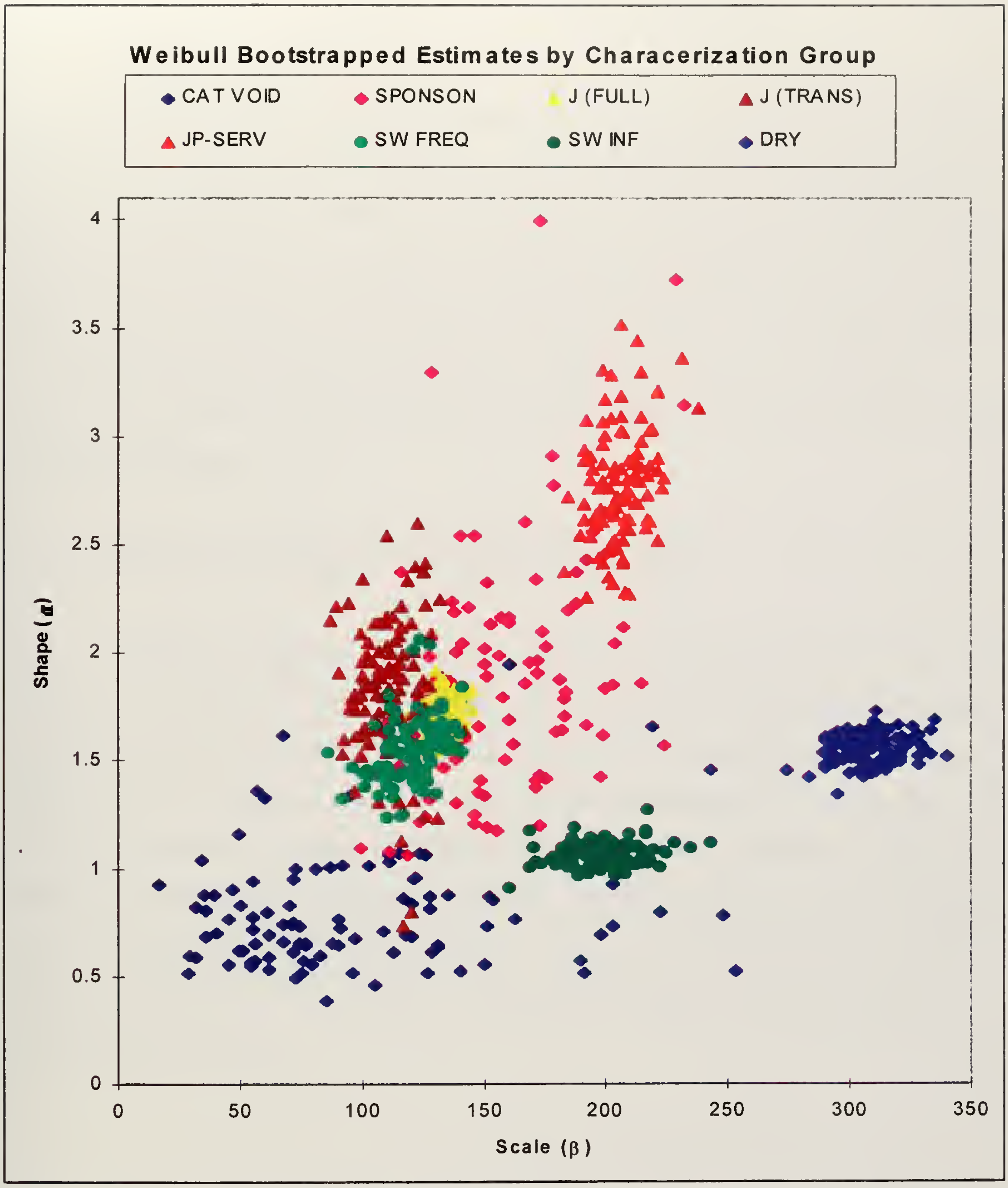

Figure V-6 Bootstrapped estimates for Weibull parameters by characterization group.

VI. A LIFE-CYCLE INSPECTION MODEL

The previous chapters discuss the methodology used for estimating the survival function for each group of tanks and voids. This section uses those estimates to show how a life-cycle inspection model can be developed. This model is intended to be used as a decision aid for inspection planning. It considers the various options of tank and void inspection for a 96 month period from dry-docking availability to dry-docking availability. This model is not a comprehensive maintenance planning tool, but it does include the options of overhauling without inspecting and neither inspecting nor overhauling of a tank as inspection options.

A. THE SINGLE PERIOD INSPECTION DECISION

The influence diagram in Figure VI-1 describes the inspection decision process for a 96 month period between dry-docking opportunities where inspection opportunities are available at 24 month intervals. The inspection decision model can be adapted to varying lengths of time between overhaul periods and inspection opportunities. This includes, for example, the addition or deletion of inspection opportunities as each ship's schedule dictates. Inspection planning decisions are always subject to the four elements of influence (decision options, forecast status, actual status, and results) shown in Figure VI-1. The function and interaction of each element in the influence diagram (Marshal and Oliver, 1995) is explained below.

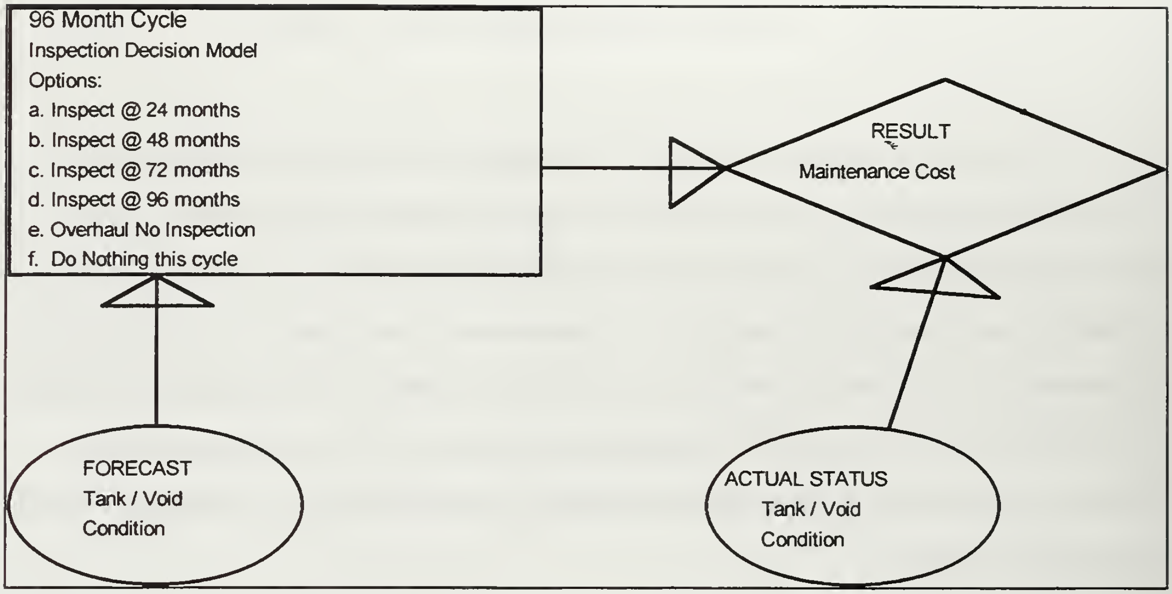

Figure VI-1 Influence Diagram for single 96 month period (between Overhaul opportunities) Tank Inspection Decision.

1. Decision options

At each 24 month inspection opportunity only a portion of the ship's total tanks and voids can be inspected. This decision model includes the options to inspect only at 24 months, 48 months, 72 months, or at 96 months. The option to inspect a tank more than once is not available. This is realistic because tanks found to be failed at an inspection are flagged for overhaul and not inspected again prior to that overhaul. For tanks that are inspected and found to be in good condition, limited resources preclude reinspection before the overhaul period. The option to overhaul a tank at the end of the period (without inspecting it during the period), and the option to neither inspect nor overhaul a tank are also included.

2. Forecast Probability of Failure

At the end of each 96 month period the coating age of every tank is known. The age of all tanks overhauled is reset to zero (overhauled as good as new), and the age of all tanks not overhauled continues from their last date of overhaul. From the survival functions (estimated in Chapter V) the probability of coating failure in the next 24 month period between inspection opportunities is estimated based on the age of the tank. For example, if a tank is overhauled at 96 months then its probability of failing in the 24 month period following overhaul is the same as for a new tank. For a tank inspected but not overhauled at 96 months, the probability that it will fail in the next 24 months is the conditional probability that it will fail before 120 months given that it survived 96 months. Thus the probability of failure for each tank is continually updated throughout its life.

3. Actual Status

The actual status of tank coating condition is a random event whose probability of outcome is estimated by the forecast probability of failure, but whose certainty cannot be known without an inspection. The action taken in the decision option does not influence the actual condition of the tank during the maintenance period in question but may affect it in the next period. For example, the decision to overhaul sets the actual condition at not failed immediately following overhaul at the end of the period.

4. Results

The results in this model are the maintenance costs incurred from the actions taken and actual status at the end of the 96 month inspection period. The results include the costs of inspection, repairs, and a penalty cost, for missing an overhaul opportunity when one is needed. Assessing a penalty cost precludes the naïve decision option of never making inspections and thereby incurring no costs. The decision to overhaul a tank once it's condition has been found to be failed is a maintenance decision whose outcome depends upon factors not considered in this inspection model. For purposes of modeling it is assumed that, once identified, all failed tanks are overhauled at the end of the 96 month period.

B. MAINTENANCE MODEL COSTS

Maintenance costs are calculated from the average cost of inspection and repair of a typical JP-5 stowage tank. In this model the cost of inspection is $5,000 and the cost of pre-planned overhaul is $60,000. In reality, both the overhaul and inspection costs have fixed and variable sub-portions. The fixed portion accounts for the planning and set-up required to inspect or repair any tank within a given characterization group. The variable portion is directly related to the surface area to be cleaned and / or overhauled. This portion accounts for approximately 90% of the overhaul cost. The variable portion of the costs is a function of the volume and surface area of a tank. These differ considerably between tanks even within the same characterization group. But, the magnitude in cost of inspection verses repair (1:12) is relatively constant for all tanks. Sensitivity analysis performed in Section E of this chapter further investigates the effects of changing overhaul and inspection costs on the inspection decision. The costs may be changed to meet more specific values of individual tanks in question. However, the use of relative costs is justified in the model because as long as the ratio of overhaul to inspection costs is 12:1, the actual magnitude of the costs does not affect the results of the decision model. The cost of performing a new work overhaul is modeled as twice the cost of performing a pre planned overhaul. The cost of missing an overhaul opportunity is modeled as equal to the tank's criticality factor times the overhaul cost.

C. A DECISION AT ONE INSPECTION OPPORTUNITY

The elementary decision model makes use of a decision sapling (Marshal and Oliver, 1995). A decision sapling incorporates the elements of the influence diagram into a linear format which clearly defines their interactions and results. The 96 month inspection decision model can be formulated as a decision tree made up of multiple saplings. Each sapling represents the decision to inspect or not and the results for one inspection opportunity. Understanding the interaction within the decision sapling provides the basic building block from which more elaborate models (such as the 96 month model) are constructed.

Figure VI-2 shows the decision sapling for the decision to inspect a tank at an arbitrary time in life. The decision makers objective is to minimize expected maintenance costs (including the artificial penalty cost of missing a needed overhaul) by choosing the inspection option with the smallest expected cost. In a model with more than two decision options this objective results in an optimal and multiple sub-optimal options. The random event of tank coating failure is the same regardless of the decision to inspect or not inspect. But, as illustrated in the figure, the combination of this random event and the decision taken provides four possible results.

The four possible results of this model are consistent with those of the larger decision tree and are discussed here:

GI Tank was inspected and found to be in good condition. This results in the following:

1. Cost of performing the inspection.
2. Specific tank condition becomes known and can be used to update and refine the estimate of the survival function for the group.
3. The forecast failure probability for this tank may be updated based on the age at inspection and the estimated survival function for the group.

BI Tank was inspected and found to be in need of coating overhaul. This results in the following:

1. Cost of performing the inspection.
2. Specific tank condition becomes known and can be used to update and refine the estimate of the survival function for the group.
3. If the ship is not currently in a dry-docking availability the tank can be scheduled for coating overhaul as pre-planned work at the next dry-docking availability.
4. If the ship is currently in a dry-docking availability the tank can be scheduled for coating overhaul as new-work or growth in the current availability or as pre-planned work in the next dry-docking availability. This decision will depend upon the criticality of the tank, and available resources.
5. The tank will be flagged for overhaul and no further inspections should be needed or performed until post overhaul close-out.

GN Tank was not inspected but was in good condition. This results in the following:

1. Specific tank condition remains unknown and additional information about the survival function for the group not collected.
2. Expected age of failure for this tank not updated.

BN Tank was not inspected and is in need of coating overhaul. This results in the following:

1. Cost of performing the inspection not expended.
2. Specific tank condition remains unknown and additional information about the survival function for the group not collected.
3. If the ship is not in a dry-docking availability one (of perhaps several) opportunities for scheduling coating overhaul as pre-planned work at the next dry-docking availability will be missed.

4. If the ship is currently in a dry-docking availability the opportunity for coating overhaul, as new-work or growth, in the current availability is missed.

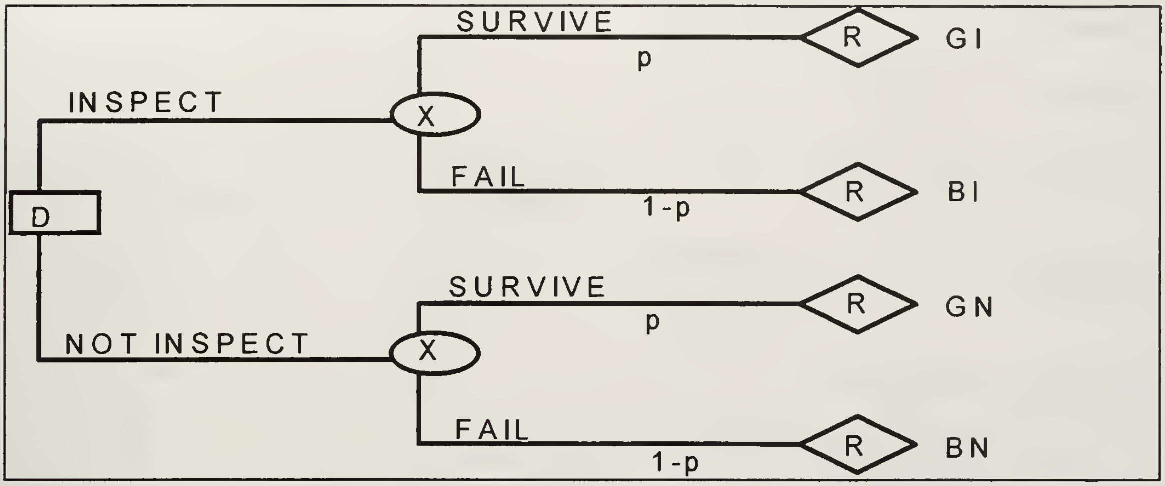

Figure VI-2 Decision Sapling for evaluating the single opportunity decision to inspect or not inspect.

Results from each random event are be rolled-back (Marshal and Oliver1995) to compute an expected cost at that event node. Similarly the expected costs of each decision option are rolled back to the decision node where the optimal decision is the decision option which leads to the minimum expected cost. (The model software used is DATA version 2.6.4 by TreAge Software Inc.).

D. THE 96 MONTH TANK INSPECTION DECISION MODEL

Incorporating the model for the 96 month period, the costs, and the model for a single inspection opportunity into a working decision tool requires the full enumeration of decision options and resulting costs. This gives a decision model with fourteen result nodes. The model incorporates the full range of options. For example a tank inspected and satisfactory at say month 24 can fail prior to the 96 month overhaul opportunity. If this tank is not inspected again it results in a missed overhaul opportunity for that tank. The 96 month inspection decision model for the JP-SERV group tanks as appears on the screen when using the DATA software is shown in Figure VI-3. This Figure shows the process for determining action on a typical JP-SERV tank based on the tanks inspection and repair costs, its criticality, and the estimated survival probabilities of the tank from Chapter V.

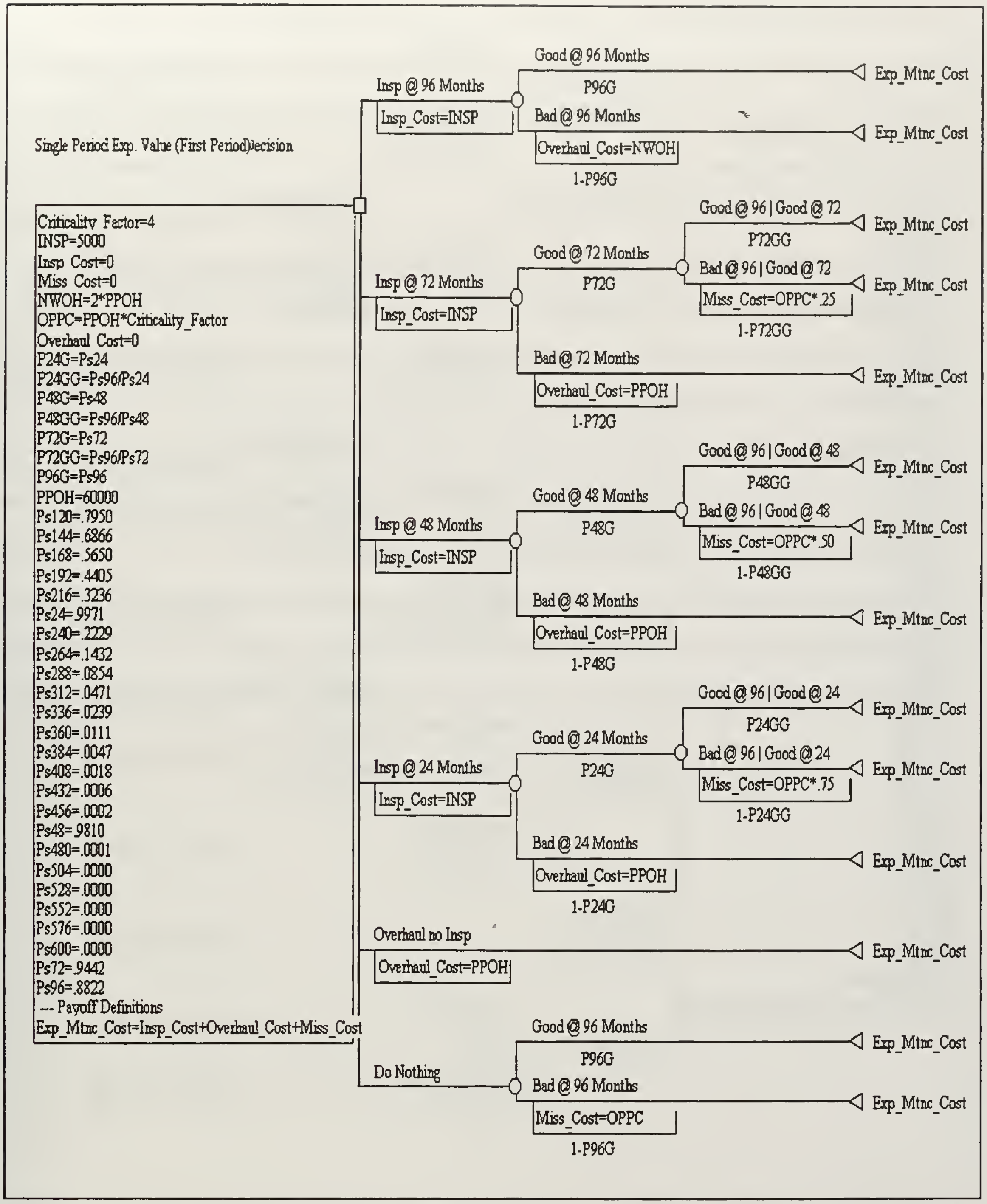

Figure VI-3 96 month Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

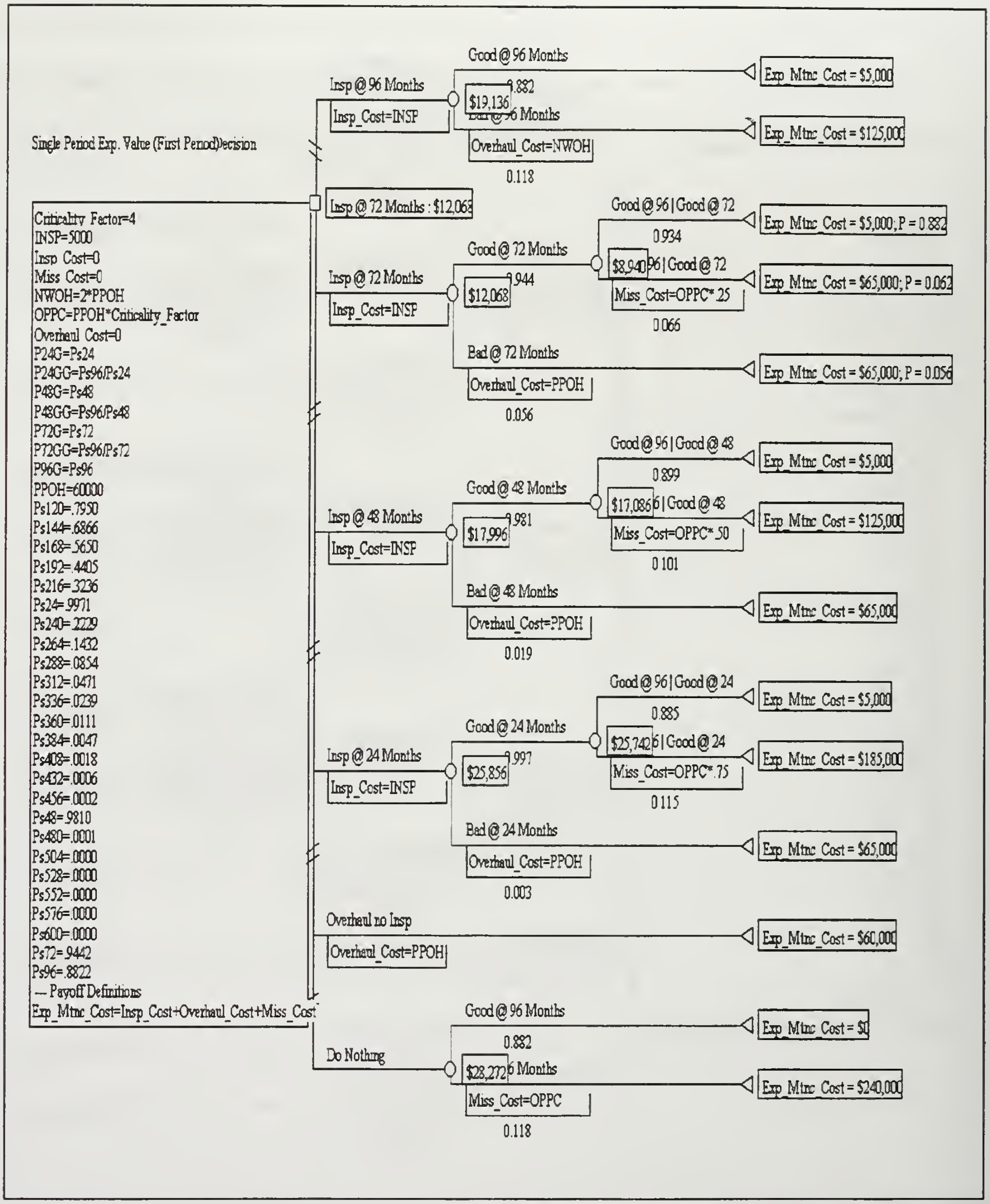

Figure VI-4 Roll-back of Tank Inspection Decision Model showing expected costs and recommended action to take in JP-SERVICE tanks during the first 96 month period of tank coating life.

The Roll-back algorithm computes the expected cost at each chance node then identifies the decision option that best meets the objective. Sub-optimal decision options are indicated by double hash mark. The optimal first period decision option is to inspect at the 72 month opportunity (where if the tank needs overhaul it can be scheduled as pre-planned work while making the chance of missing a needed overhaul small).

Expected costs change as the tank ages since the probability of failure increases with tank life. Recalculation of the decision tree for each 96 month period between overhauls gives the optimal and sub-optimal inspection options as the tank ages. Figure VI-5 shows how this results in varying optimal decisions with tank life. In this figure the expected costs are plotted for each of the six possible decision options as a function of the 96 month period. At the beginning of the i^{th} 96 month period the age of the tank is set to $i * 96 \{ i = 1, 2, \dots, 5 \}$. The expected costs are costs incurred only during a particular 96 month period. Here, overhaul without inspection is the most expensive option in the first period due to the high probability of surviving that period. As the tank ages the cost of doing nothing grows and dominates the rest of the decision options due to decreased probability of survival.

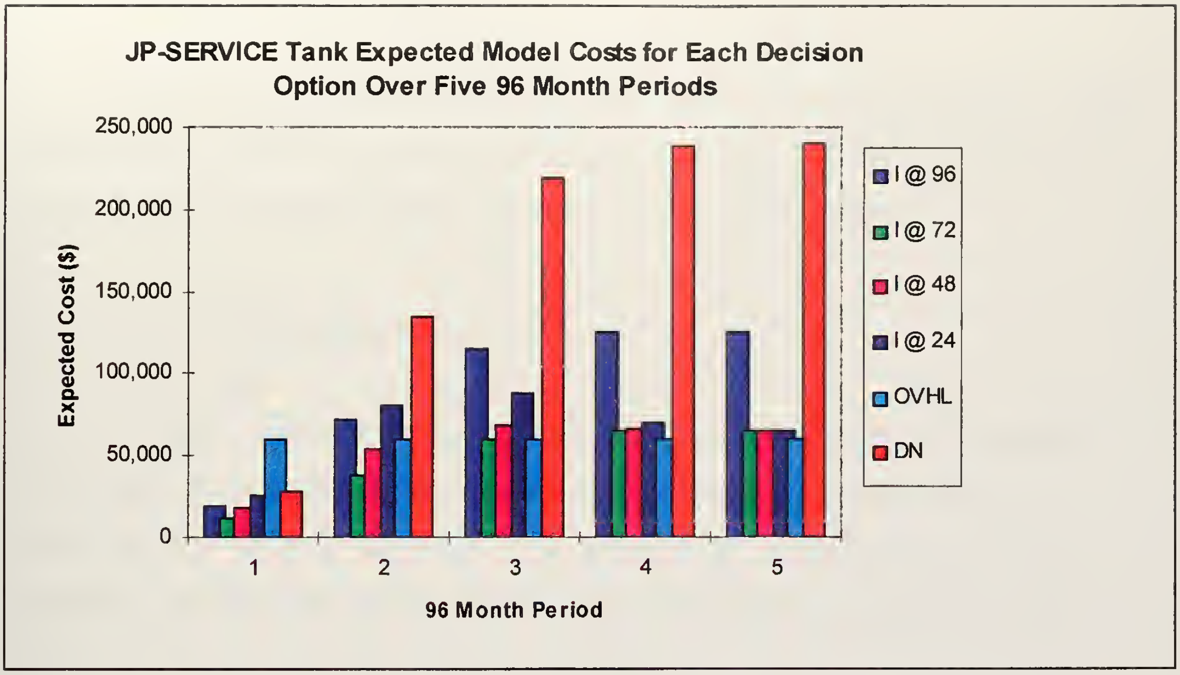

Figure VI-5 Expected Costs of Tank Inspection Decisions as determined for each Overhaul opportunity to Overhaul opportunity period of tank life (96 month overhaul cycle with 24 month inspection opportunities shown).

Appendices D through M illustrate the changing optimal decisions as tank life increases for each group. The best option early in tank life is to inspect (do nothing in some less critical groups) but as the tank ages the optimal decision changes to overhaul without inspection. In addition, late in the tank life the most costly decisions are to do nothing or inspect only at 96 months. For the more critical tanks, the impact of missing a needed overhaul opportunity becomes the driving force in the decision. For some groups no calculation is made beyond the third period because the estimated probability of survival for those groups beyond period four is zero. Also note that there is no calculation for LUBE OIL tanks or CAT WING voids because the survival function for those groups remains to be estimated.

E. MODEL SENSITIVITY

This model is sensitive to each of its input factors. The most significant of which are the tank's criticality factor and its survival function S(t). Sensitivity analysis of the model is performed using JP-SERV group for the first 96 month period.

1. Survival Function

A simplification of the model is required in order to analyze how the survival function affects the expected costs. The model is simplified to consider only one inspection opportunity for the period. The probability of survival is taken to be the probability p of surviving the entire 96 month period. With these simplifications the expected costs for four decision options are compared. These decision options are:

1. Inspect the tank early enough in the 96 month period to schedule overhaul as pre-planned work.
2. Inspect the tank after the start of the overhaul availability thus requiring any overhaul of the tank to be scheduled as new work.
3. Overhaul the tank without inspection (scheduled as pre-planned work).
4. Do nothing.

Figure VI-6 shows the expected cost for the first 96 month period. As p changes there is a change in the optimal decision. These changes are intuitive in the sense that it is optimal to do nothing to a new tank, overhaul an old tank, and inspect those tanks in between.

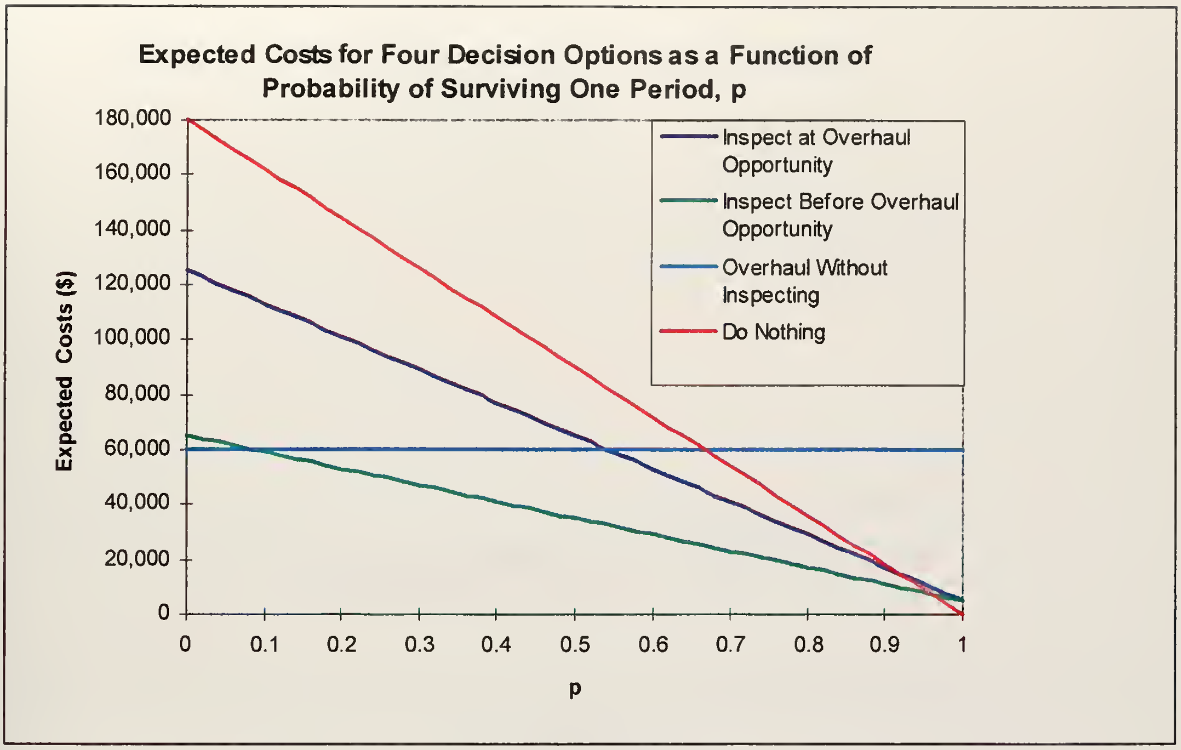

Figure VI-6 Sensitivity of the Inspection Decision Model to survival probability.

2. Criticality Factor

Assigning a value to a particular level of the criticality factor is up to the model user. Chapter IV Section C describes the authors initial assigned value as a ranked level of impact given the failure of any tank in each characterization group. This is the most sensitive user input. Figure VI-7 shows how the criticality factor affects the optimal decision. This figure shows that the costs increase and become more spread out as the criticality factor increases. The difference in expected costs is driven by the effect of missing a needed overhaul. As the level of criticality increases the potential for tank failure after the last inspection but before the overhaul opportunity becomes a more significant factor. Note that there is no chance of missing an overhaul if the inspection is at the 96 month opportunity hence it's constant value.

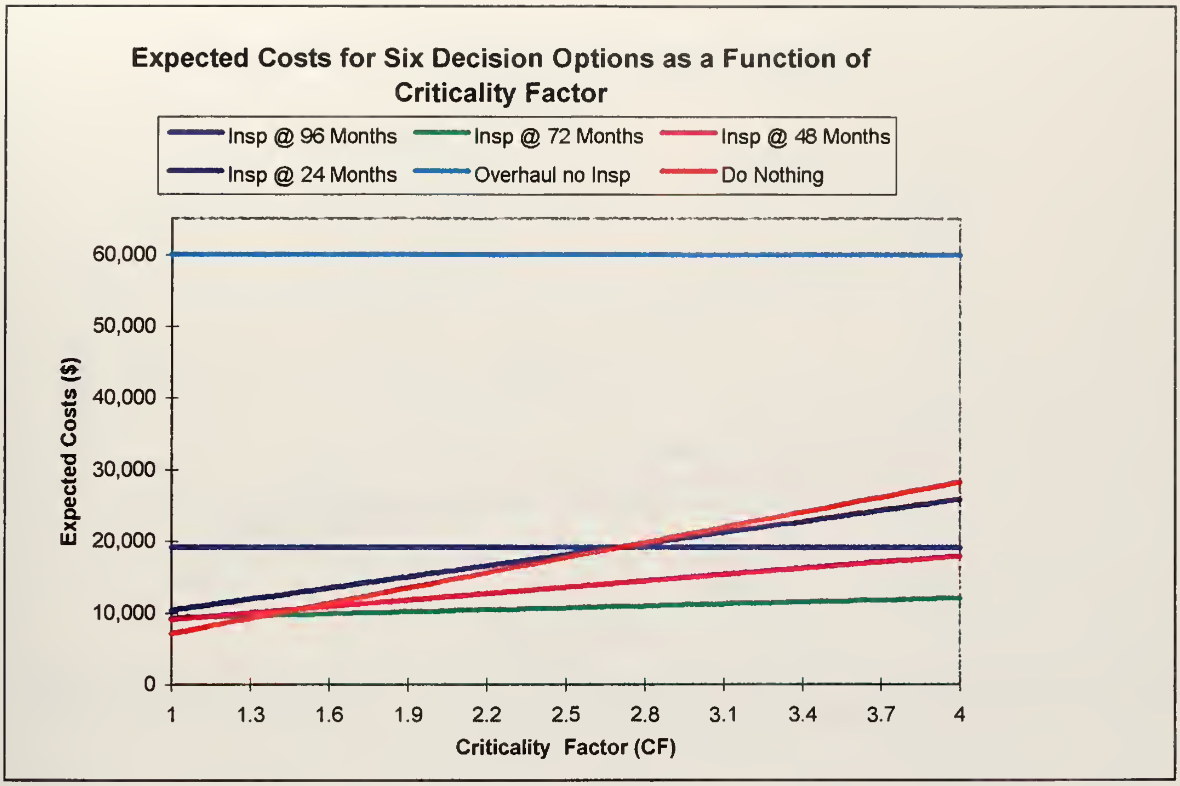

Figure VI-7 Sensitivity of Inspection Decision Model to Criticality Factor.

3. Overhaul Cost

Figure VI-8 shows the sensitivity of the decision option to overhaul cost. The costs of overhaul for the JP-5 tanks range from $25,000 to $81,000. While expected costs vary linearly with overhaul cost the optimal decision is the same over most of the range. For this group it is best to drive maintenance by inspection, regardless of the overhaul costs.

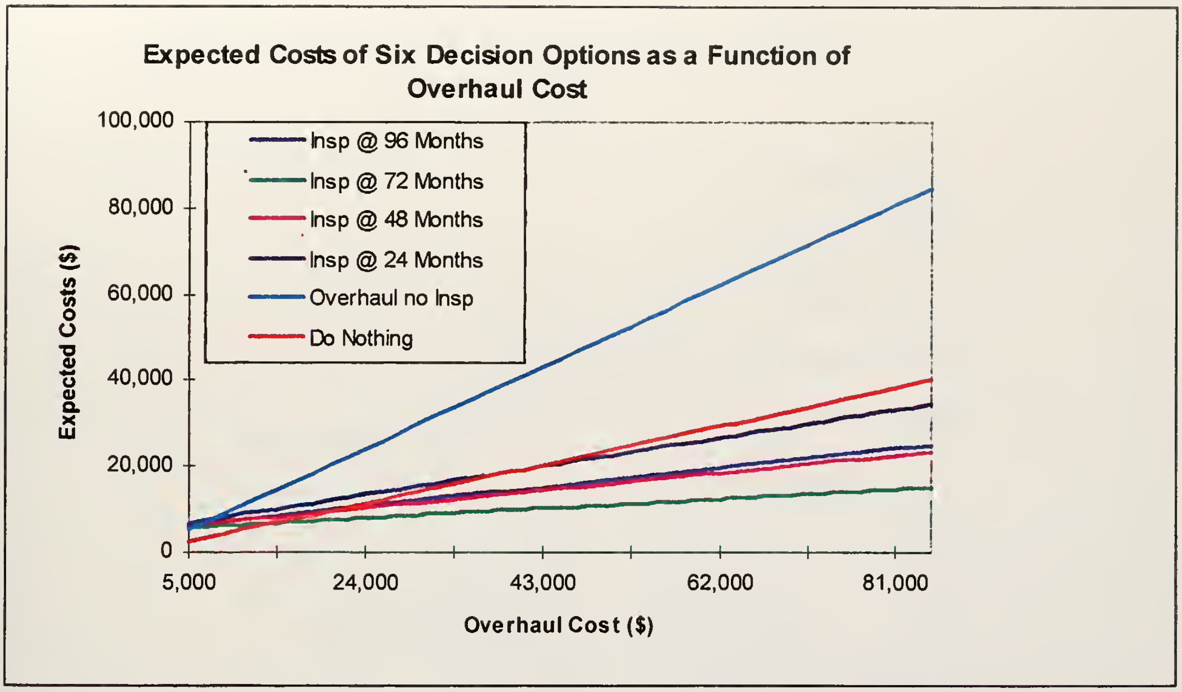

Figure VI-8 Sensitivity of the Inspection Decision Model to Overhaul Cost.

4. Inspection Cost

The costs of inspection for the JP-5 tanks range from $0 to $10,000. Figure VI-9 shows the sensitivity of the decision options to inspection cost. Again, while the expected costs vary linearly with inspection costs the optimal decision remains the same. For this group it is best to drive maintenance by inspection, regardless of the inspection cost.

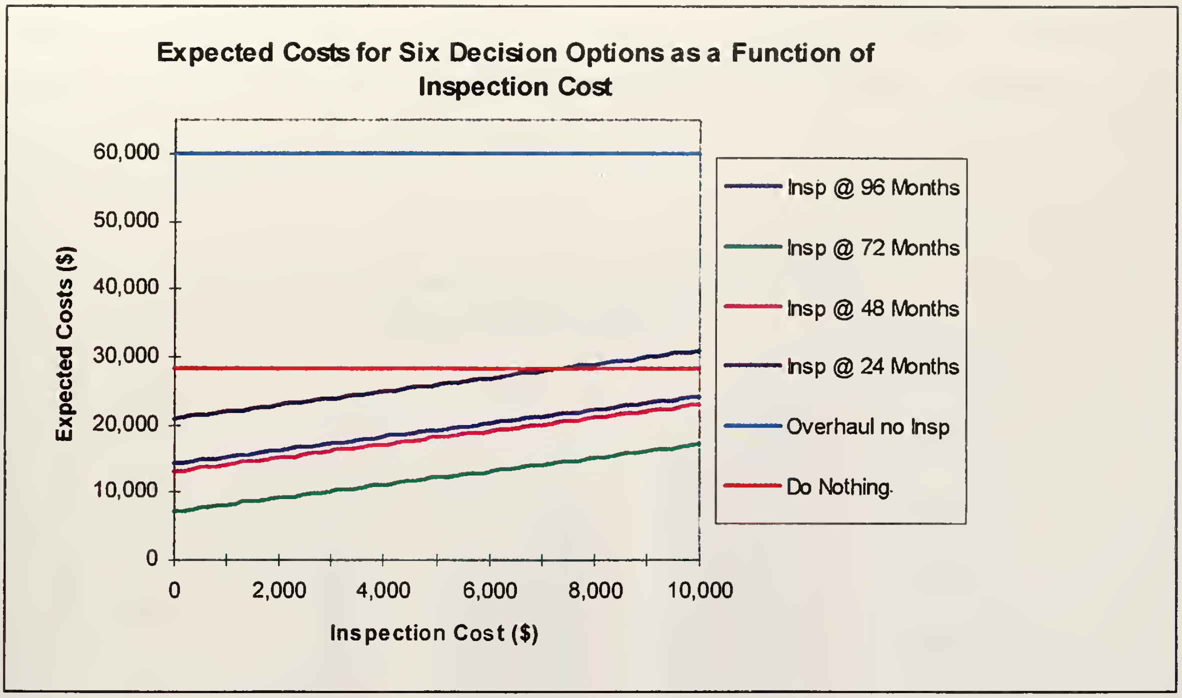

Figure VI-9 Sensitivity of the Inspection Decision Model to Inspection Cost.

F. COMPARISON OF THE ONE, TWO, AND THREE PERIOD INSPECTION DECISION MODELS

The 96 month Inspection Decision Model is a decision aide to help the maintenance planner decide upon near term inspection actions. It is intended to be used iteratively after each overhaul availability. The single period model has 14 possible paths. Multiple period models contain 14^n possible paths (where n is the number of periods). Expansion of this model beyond three periods is not possible with the current software package (DATA version 2.6.4 by TreAge Software Inc.). Figure VI-10 shows the results of the one, two and three period models. These results support the conjecture that the downstream effects of a multiple period model do not significantly change the current period decision given by the single period model. The basic decision of whether to inspect, overhaul, or do nothing remains unchanged as model length increases. Timing of when to inspect does change somewhat. The optimal inspection time (72 months) remains constant while sub-optimal inspection at 48 months becomes less preferable than

inspection at 96 months as the model length increases. However, an order of magnitude difference exists between expected costs of performing either inspection compared to the expected costs of the do nothing or overhaul options.

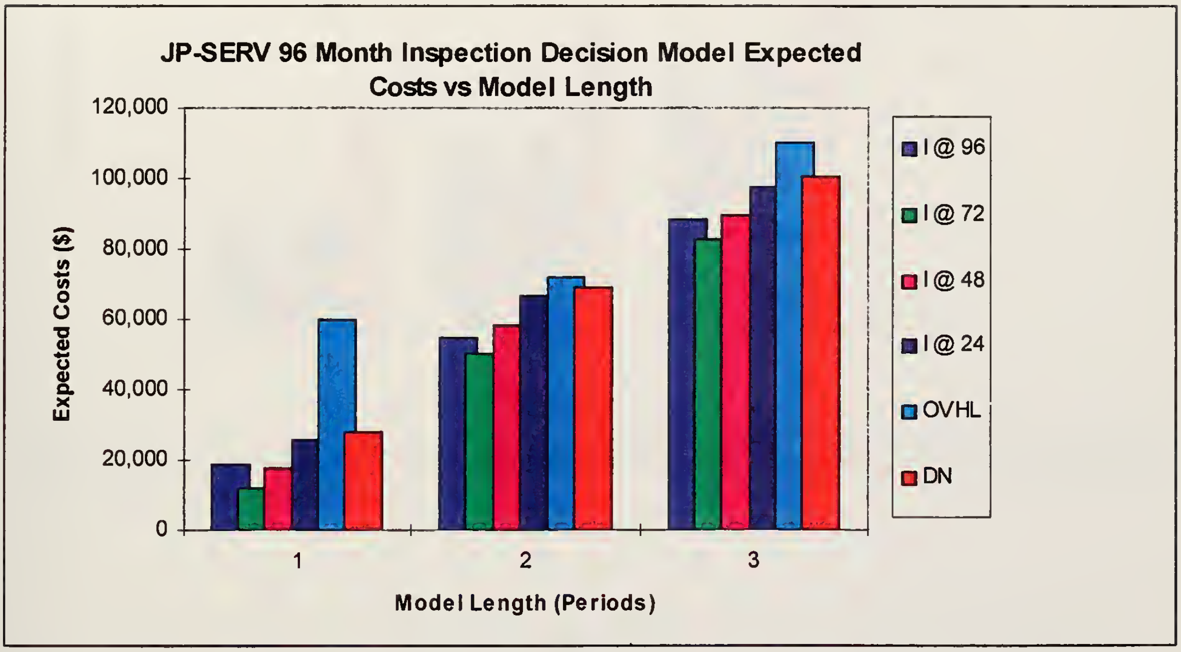

Figure VI-10 Comparison of decision option preferences for JP-SERV by period length of 96 month Inspection Decision Model.

Repeat of this comparison for the CAT EXH group results in the same consistency. Figure VI-11 shows the results. The basic decision of whether to inspect, overhaul without inspection, or do nothing remains unchanged as the model length increases from one to three periods.

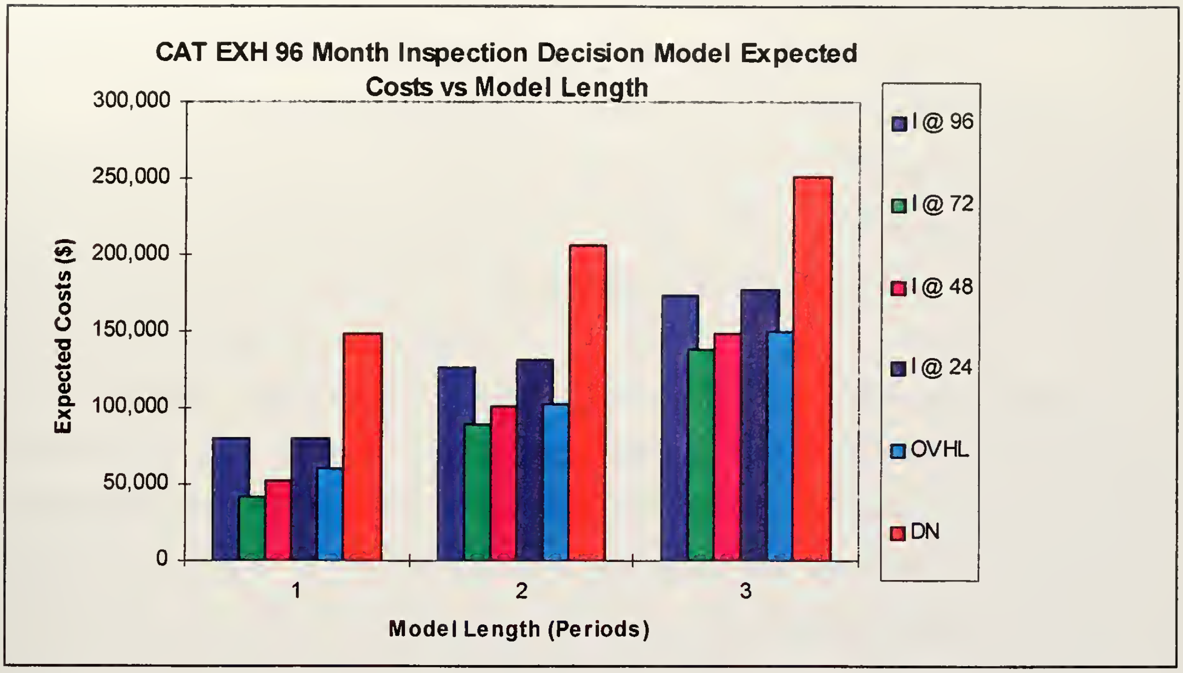

Figure VI-11 Comparison of decision option preferences for CAT EXH by period length of 96 month Inspection Decision Model.

The only difference in inputs between the CAT EXH group and the JP-SERV group is their survival functions, but their expected costs and optimal decisions differ significantly. It is evident that changes in survival function effect the optimal decision much more than extending the model from a single period to several periods. Hence, the single period model is both adequate and robust for current planning needs.

G. INSPECTION DECISION MODEL SUMMARY

This chapter develops an analytic tool for determining inspection times for a tank or void in a hypothetical 96 month period. This hypothetical period allows inspections at each 24 month interval. The model inputs are survival function, criticality, overhaul cost, and inspection cost. The choice of inspection times is most sensitive to the survival function and criticality.

Even though this model is not entirely realistic, some observations extend to the general case. The two most expensive options are to overhaul tanks with high probability

of survival and to do nothing to tanks with low probability of survival. Less costly options are almost always to drive maintenance by inspection in the 96 month period.

The real benefit of this model is to see the long term effects of inspection decisions on expected costs. Maintenance managers have not had a tool to quantify costs over more than one inspection interval or to compare the costs of several options over the different tank groups. This allows the maintenance managers to try different options and to justify long term costs and budget.

Practical application of this model requires substitution of the actual overhaul period length, times within that period when inspections may be performed, and the actual probability of failure at each time within the period. When used to model a single tank the actual cost of specifically inspecting and overhauling that tank should also be substituted. This model can be adapted to include more or fewer inspection opportunities, secondary inspection opportunities, and other realities of the actual inspection decision processes. For example, for highly critical tanks such as JP-SERV, the option to schedule overhaul then inspect at 96 months can be included. This option allows for pre-planning overhaul for tanks that have failed and the ability to cancel overhaul on tanks that prove to be good.

The larger problem is to decide which tanks and voids to inspect, when the optimal decision cannot be made on a tank by tank basis. This problem can be solved by a linear program (Bazaraa, Jarvis, and Sherali 1990) with the decision option costs as inputs. Formulating this larger problem quantitatively is premature until the inputs, specifically the estimates of tank and void survival functions, are credible.

Even in the single tank decision models, great care should be exercised when based on the survival functions of Chapter V. The decision option outputs from this model can be no better than the quality of data upon which the survival functions are determined, and may be substantially worse.

VII. SAMPLING METHODOLOGY

In the early portion of tank life the optimal decision is to not inspect at the 24 month availabilities. This optimal decision is sensitive to the probability of surviving the first period. Current estimates of this probability are based on a few historical records of questionable quality. Until more is known about the survival probabilities of tanks and voids it is still prudent to inspect enough tanks of each group to ensure that the probability of survival is large enough (usually > 90%) that the optimal decision remains the same.

An approach for determining the number of tanks to inspect is found in the CVN 71 FY 1997 EDSRA and CVN 73 FY 1997 SRA sampling plans provided to PERA(CV) at the beginning of this study (Thornell and Whitaker "Development of Tank and Void Inspection Recommendations for CVN 69, 71, 73"). Both CVN 71 and CVN 73 are young enough (commissioned in October 1986 and July 1992 respectively) that the expert opinion is that at most 5 to 10% of their tanks will fail by their FY 1997 inspection opportunity. Thus, the optimal policy suggests no inspections. However, at the time the plans were developed there was no data from these or other ships to support the 5 or 10% figures. The data analyzed in chapter V became available the week of 01 April and full analysis was not completed in time to be of benefit to these plans.

In both sampling plans tanks and voids are stratified according to the characterization groups of Chapter III. Within each group, the smallest sample size was found to meet a particular criteria. The criteria varied from group to group depending on the number in the group, it's criticality, and what was known about the group prior to the recommendation.

A. ACCEPTANCE SAMPLING

For the groups with criticality factor lower than 4 (J (FULL), LUBE OIL, SEA WTR (FREQ), SEA WTR (INF), CAT WING VOIDS, SPONSON, and DRY) the criteria used is analogous to that of acceptance sampling (Duncan 1986). Here the goal is to have a sample size large enough to detect groups for which the true proportion of failed tanks is higher than the value hypothesized by the planning managers. Levels of significance and power are chosen, for each group and are given in the sampling plan. Specifically, let r be the unknown number of failed tanks in a group of size N. Test the null hypothesis that $r \le r_0$ verses the alternative that $r > r_0$ where r_0 is close to some percentage of N, typically 10%. The test statistic for this test is X, the number of failed tanks out of a sample of size n where X has a Hypergeometric distribution with parameters N, r, n. For this test the decision rule is of the form reject H_0 (i.e., decide that $r > r_0$) if $X \ge c$. The critical value c and sample size n are found simultaneously by solving:

$$P(X \ge c \mid r = r_0) = \alpha$$

$$P(X \ge c \mid r = r_1) = 1 - \beta$$

where α is the level of significance and $1-\beta$ is the power of the test when $r = r_1$,and $r_1 > r_0$.

The solution of n and c require enumerating Hypergeometric probabilities for each possible n and for both r_0 and r_1. This gives sample sizes slightly smaller than found in the usual acceptance sampling plans (IAW Mil Std 105D) which are based on a Normal approximation of the distribution.

B. CONFIDENCE INTERVALS

For groups of criticality four or those for which there was some evidence (perhaps anecdotal) that the percentage of failed tanks is higher than expected, the sample size is chosen to give a confidence interval for the population of failed tanks with a specified width and level of confidence. For the smaller groups the sample size was computed to give a lower confidence band for the true number of failed tanks with a specified level of confidence. There is no closed form expression for exact Hypergeometric confidence intervals thus the sample size is determined iteratively. For larger groups the sample size was chosen to give a certain width two sided approximate confidence interval for r. This interval is given by:

$$b \pm 2 * Z_{(\alpha/2)} \sqrt{\frac{b(N-b)}{n} \quad \frac{(N-n)}{(N-1)}} ,$$

where $Z_{(a/2)}$ is the (1-α/2) quantile of a Standard Normal and b = N*(X/n) is the MLE for r.

C. SAMPLING

Once sample sizes for each group are determined, a simple random sample of tanks is selected. This sample is generated using a computer to select tanks at random without replacement. Included in the recommendations are the list of tank and void designation numbers of those selected for inspection. The fact that tanks were chosen at random within each group is an important and key feature of the sampling plan. This allows for unbiased estimates of the proportion of failed tanks or inference with the desired power and level of significance. Without the random sampling, bias can be introduced into the estimates of the proportion of failed tanks. As in the case of the SEA WTR (INF) tanks discussed in Chapter V. If random sampling is performed at each opportunity that the group of tanks is inspected, then this data can be used to form unbiased estimates of the survival function.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

A major contribution of this thesis is the stratification of Nimitz class aircraft carrier tanks and voids into ten groups along with the assignment of a criticality factor to each group. These groups were determined based on engineering considerations. Choice of these groups is validated by both expert opinion and the data analysis of Chapter V. These groups and criticality factors can be extended to other classes of ships and have already been used for conventional powered aircraft carriers CV 63 and CV 64.

A second contribution is the demonstration of methods to estimate the survival function of tank and void coating lifetimes based on the records found in the T&VDB. All of this data is interval censored. Analysis of the data needs to account for this censoring which includes coating lifetimes of tanks that have failed between inspections, prior to the first inspection, and those that have not failed as of their last inspection. The actual estimates of survival function given in Chapter V are based on data of questionable quality.

The third contribution is development of a decision tool to plan inspections of a tank or void in the 96 month period between overhauls. While this model is preliminary and based on the data of Chapter V, it does demonstrate the cost effectiveness of driving maintenance by inspection of tanks and voids between overhaul opportunities. It also provides a methodology for quantifying long term costs of various maintenance options. This gives the managers a tool to plan and budget over multiyear periods. There is enough flexibility in this model so that it can be tailored to a specific tank or void and to include decision options not considered in this thesis. In addition, this model can form the foundation of an optimization model that plans inspection for multiple tank (of possibly differing ages and types) simultaneously. However, until better estimates of the survival function of coating lifetimes is available such an extension is premature.

Finally, the methods used to develop the sampling plans provided to AIRLANT for CVN 71 1997 EDSRA and CVN 73 1997 SRA are included. These sampling plans were developed to obtain unbiased estimates of the current proportion of failed tanks within each group. By using plans such as these and recording the results in the T&VDB over a long period of time and for tanks with different (and known) coating ages, unbiased estimates of the survival function for each group can be computed.

B. RECOMMENDATIONS

There are several immediate and long term recommendations and suggestions that have come to light during the research of this thesis. Some of these recommendations are not new but are included here for emphasis and completeness.

1. Immediate Recommendations:

a) Update PMS MRC cards for all tank and void inspections to specifically require that records of all inspections of tanks and voids be entered into the T&VDB. Without this, data will not be recorded reliably.

b) Establish the position of ship's Tank and Void Coordinator as a single point of contact for shipboard tank and void inspection and maintenance issues. This would be a collateral duty position similar to that of the ship's Calibration Coordinator.).

c) Establish a formal path and periodicity for data updates of PERA(CV)'s comprehensive T&VDB from the ship's T&VDB. Make this data available to the maintenance managers and analysts as quickly as possible. Establishing an FTP site or home page on the Internet with the latest version of T&VDB could serve this purpose.

d) Make the results of inspections immediately useable by the maintenance manager. A suggestion is to construct a periodic report based on T&VDB. This tracking report, with appropriate summary statistics and graphs, should be available well before every Work Definition Conference where inspection and maintenance are pre-planned for the upcoming availability. Such a report can be constructed in EXCEL using Visual Basic linked to an ACCESS compatible T&VDB. This report can easily include comparisons of inspection and maintenance options using decision tools illustrated in this thesis.

2. Long Term Recommendations Once T&VDB is Established

a) Analyses in this thesis are based on very coarse inspection data, specifically whether a tank coating failed (a condition three or four was scored) or not. When recorded, there is a wealth of information that results from inspections. For example, there are fields in the T&VDB for recording the actual condition of the coating (1, 2, 3, or 4) as a function of position (top, sides, bottom). These can be used to refine the survival analysis to better predict how long a tank will last in its' current state and what the most likely failure will be. All of the information in the T&VDB needs to be exploited.

b) Tank coating survival functions should be updated for each ship based on its T&VDB data. This tailors analysis to each ship's condition functions rather than relying on aggregate survival function estimates for the class.

c) Explore tradeoffs between options based on new technology such as:

(1) Improved coating and cathodic protection materials.

(2) New methods of inspection such as using a fiber-optic scope to inspect without personnel entering the actual tank.

(3) Collecting different types of information to track coating decay. For example, the use of ultrasonic probes to measure coating thickness or develop chemical analyses to monitor coating deterioration from tank contents samples.

d) Expand the decision tool to plan inspections for groups of tanks taking into account realistic budget and timing constraints.

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APPENDICES

APPENDIX A. CVN 69 INSPECTION DATA SUMMARY FOR 1986 AND 1995 INSPECTIONS

Tanks at risk of failure at approximately 105 months after overhaul			
CHAR GRP	**TOTAL # TANKS**	**# INSPECTED**	**# FAIL**
SPONSON	8	2	2
SEA WTR (FREQ)	51	25	23
J (TRANS)	30	27	19
J (FULL)	269	247	157
CAT EXH	4	3	1
JP-SERV	37	28	8
SEA WTR (INF)	102	75	23
DRY	272	38	9
CAT WING VOID	232	0	0
LUBE-OIL	53	1	0

Figure A-1 Summary of CVN 69 tanks at risk of coating failure as observed from tank inspections at approximately 105 months of coating age.

Tanks at risk of failure at approximately 210 months after overhaul			
CHAR GRP	**TOTAL # TANKS**	**# INSPECTED**	**# FAIL**
SPONSON	6	5	4
SEA WTR (FREQ)	22	5	3
J (TRANS)	6	5	4
J (FULL)	65	59	43
CAT EXH	2	0	0
JP-SERV	23	17	11
SEA WTR (INF)	60	30	12
DRY	227	20	4
CAT WING VOID	232	0	0
LUBE-OIL	53	40	0

Figure A-2 Summary of CVN 69 tanks at risk of coating failure as observed from tank inspections at approximately 105 months of coating age.

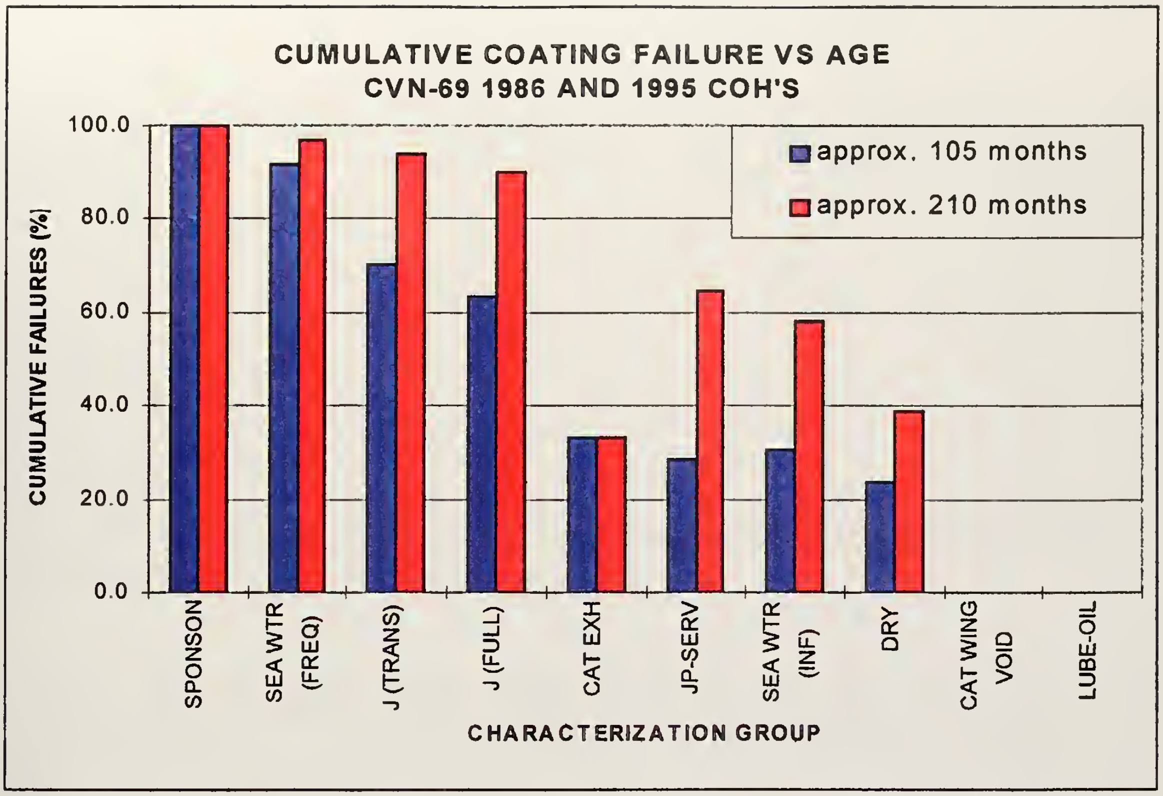


Figure A-3 Observed Cumulative Tank Coating Failure for CVN 69, by Characterization Group, for tanks inspected at approximately 105 and 210 months of Coating age.

APPENDIX B. CVN 71 INSPECTION DATA SUMMARY FOR 1989, 1991, AND 1995 INSPECTIONS

Tanks at risk of failure at approximately 34 months after overhaul			
CHAR GROUP	**TOTAL # TANKS**	**# INSPECTED**	**# FAIL**
SPONSON	8	0	0
SEA WTR (FREQ)	39	0	0
J (TRANS)	20	0	0
J (FULL)	172	1	0
CAT EXH	3	0	0
JP-SERV	30	0	0
SEA WTR (INF)	84	0	0
DRY	253	6	0
CAT WING VOID	232	0	0
LUBE-OIL	53	0	0

Figure B-1 Summary of CVN 71 tanks at risk of coating failure as observed from tank inspections at approximately 34 months of coating age.

Tanks at risk of failure at approximately 61 months after overhaul			
CHAR GROUP	**TOTAL # TANKS**	**# INSPECTED**	**# FAIL**
SPONSON	8	1	0
SEA WTR (FREQ)	39	3	0
J (TRANS)	20	0	0
J (FULL)	172	17	0
CAT EXH	3	3	2
JP-SERV	30	7	0
SEA WTR (INF)	84	11	3
DRY	253	15	1
CAT WING VOID	232	0	0
LUBE-OIL	53	0	0

Figure B-2 Summary of CVN 71 tanks at risk of coating failure as observed from tank inspections at approximately 61 months of coating age.

Tanks at risk of failure at approximately 112 months after overhaul			
CHAR GROUP	TOTAL # TANKS	# INSPECTED	# FAIL
SPONSON	8	0	0
SEA WTR (FREQ)	39	3	1
J (TRANS)	20	1	0
J (FULL)	172	6	0
CAT EXH	3	0	0
JP-SERV	30	15	0
SEA WTR (INF)	84	14	13
DRY	253	26	8
CAT WING VOID	232	0	0
LUBE-OIL	53	2	0

Figure B-3 Summary of CVN 71 tanks at risk of coating failure as observed from tank inspections at approximately 112 months of coating age.

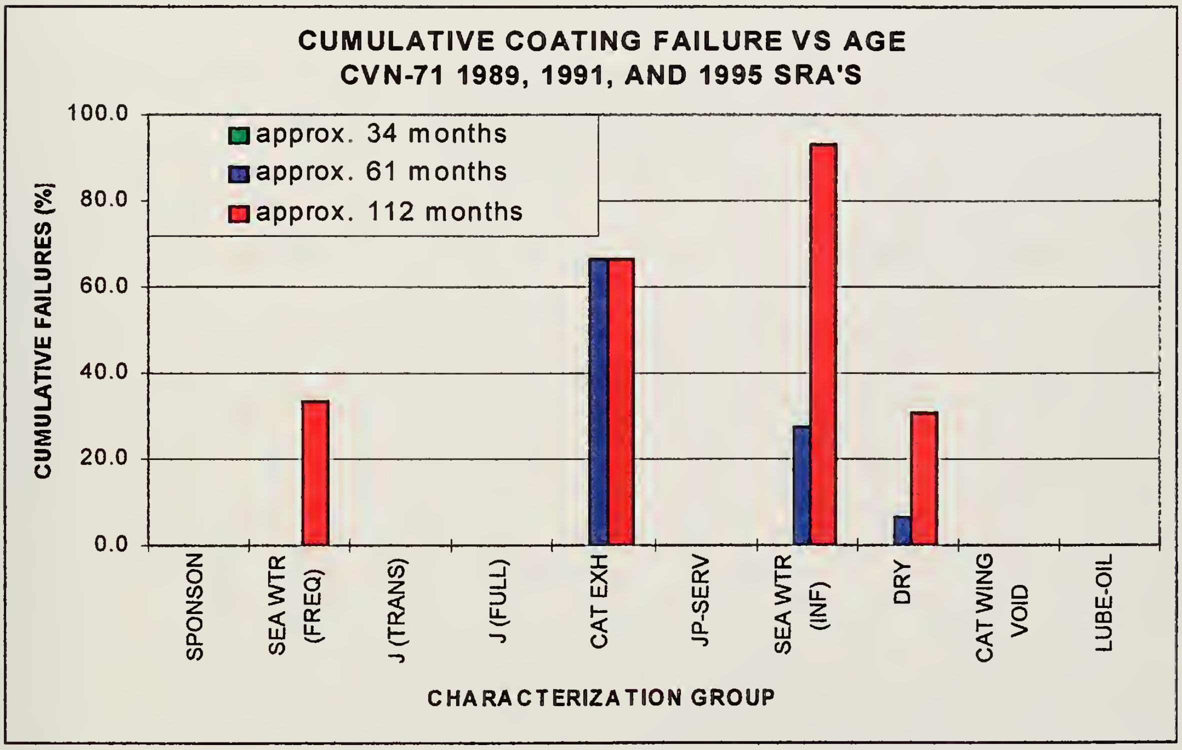


Figure B-4 Observed Cumulative Tank Coating Failure for CVN 71, by Characterization Group, for tanks inspected at approximately 34, 61, and 112 months of Coating age.

APPENDIX C. CVN 72 INSPECTION DATA SUMMARY FOR 1996 INSPECTIONS

Tanks at risk of failure at approximately 75 months after overhaul			
CHAR GRP	TOTAL # TANKS	# INSPECTED	# FAIL
SPONSON	7	2	0
SEA WTR (FREQ)	38	6	0
J (TRANS)	30	7	0
J (FULL)	167	48	0
CAT EXH	3	2	1
JP-SERV	30	10	0
SEA WTR (INF)	84	62	23
DRY	252	57	5
CAT WING VOID	232	0	0
LUBE-OIL	53	0	0

Figure C-1 Summary of CVN 72 tanks at risk of coating failure as observed from tank inspections at approximately 75 months of coating age.

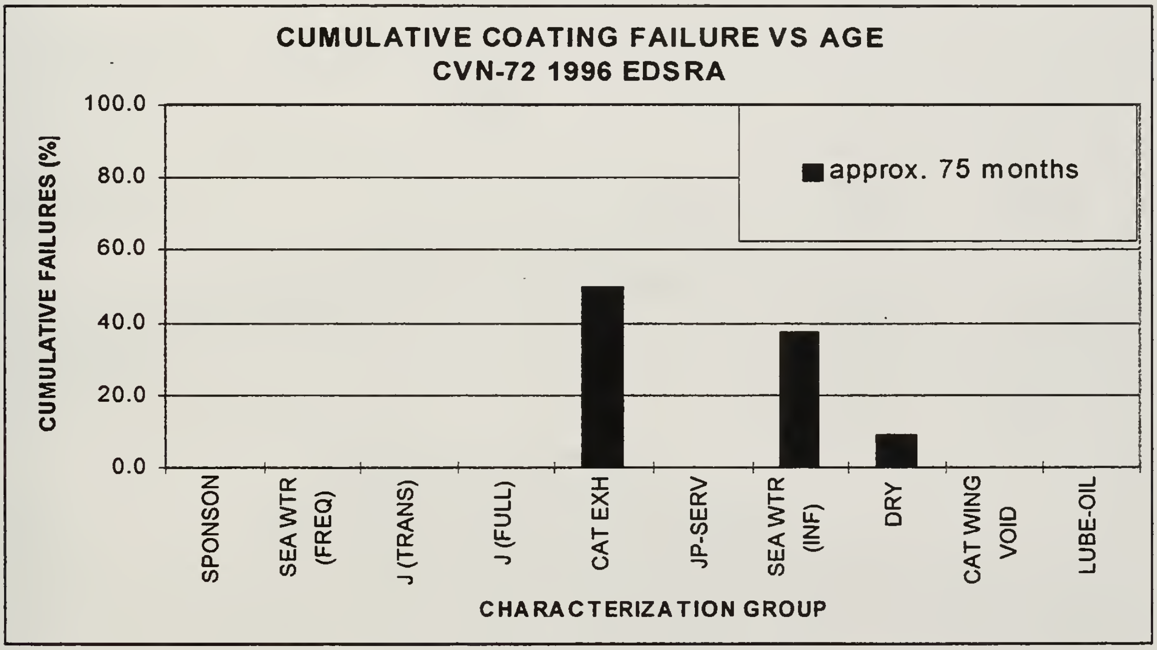


Figure C-2 Observed Cumulative Tank Coating Failure for CVN 72, by Characterization Group, for tanks inspected at approximately 75 months of Coating age.

APPENDIX D. JP-SERV GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for JP Service group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY
JP-SERV GROUP, CVN 69

DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
JP SERV	26	IOH:	7	1	11
		ICO:	16	4	6
		NICO:	3	2	2
AUX JP SERV	4	IOH:	0	0	0
		ICO:	0	0	0
		NICO:	4	0	4
COMBINED	30	IOH:	7	1	11
		ICO:	16	4	6
		NICO:	7	2	6
% FAIL			30.43	20.00	64.71
CUM % FAIL			30.43	20.00	75.45

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~105	~210
# INSPECTED	28	17
# FAILED	8	11
% (OF INSPECTED) FAILED	28.57	64.71

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure D-1 Summary of JP-SERV Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY JP-SERV GROUP, CVN 71					
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**SRA '89** (34 MOS)	**SRA '91** (61 MOS)	**SRA '95** (112 MOS)
JP SERV	26	IOH	0	0	0
		ICO	0	7	15
		NICO	26	19	11
AUX JP SERV	4	IOH	0	0	0
		ICO	0	0	0
		NICO	4	4	4
COMBINED	30	IOH	0	0	0
		ICO	0	7	15
		NICO	30	23	15
% FAIL			0.00	0.00	0.00
CUM % FAIL			0.00	0.00	0.00
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			0	7	15
# FAILED			0	0	0
% (OF INSPECTED) FAILED			0	0.00	0.00

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure D-2 Summary of JP-SERV Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
JP-SERV GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (~75 MOS)
JP SERV	26	IOH	0
		ICO	8
		NICO	16
AUX JP SERV	4	IOH	0
		ICO	2
		NICO	2
COMBINED	30	IOH	0
		ICO	10
		NICO	18
% FAIL			0
CUM % FAIL			0

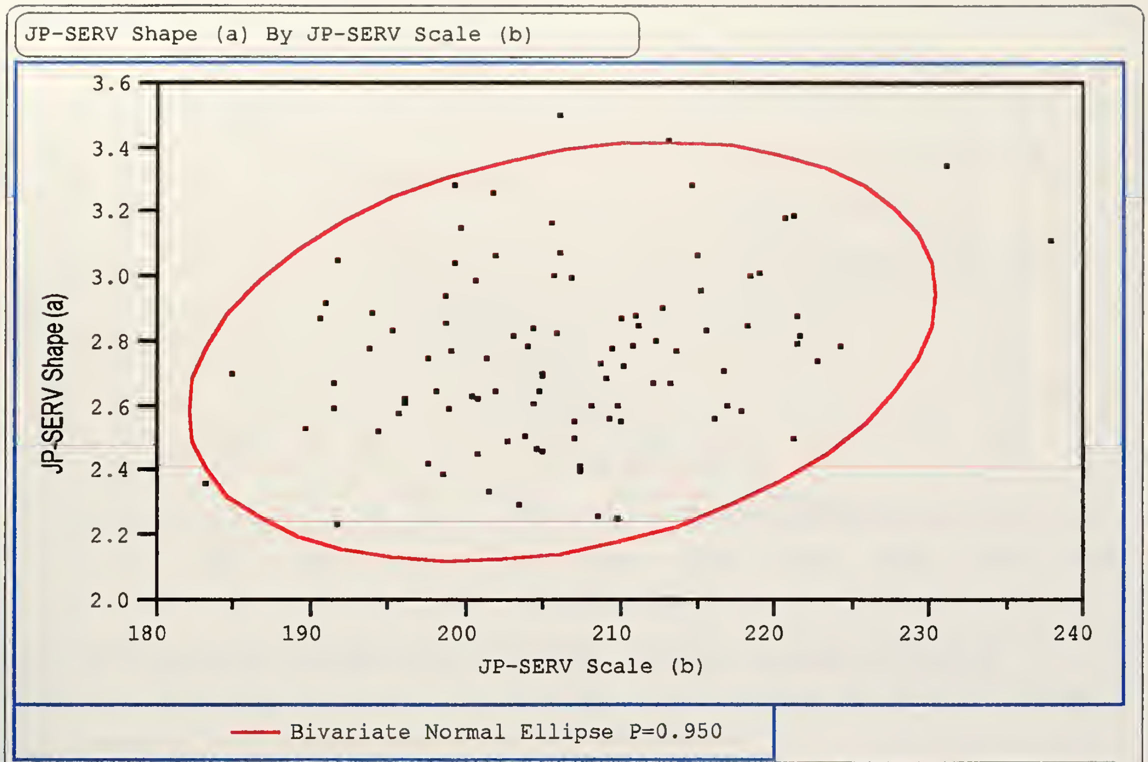
TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	10
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure D-3 Summary of JP-SERV Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
JP-SERV Scale (b)	206.29	9.88	0.28	0.005	100
JP-SERV Shape (a)	2.7768	0.27			

Figure D-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the JP-SERV group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

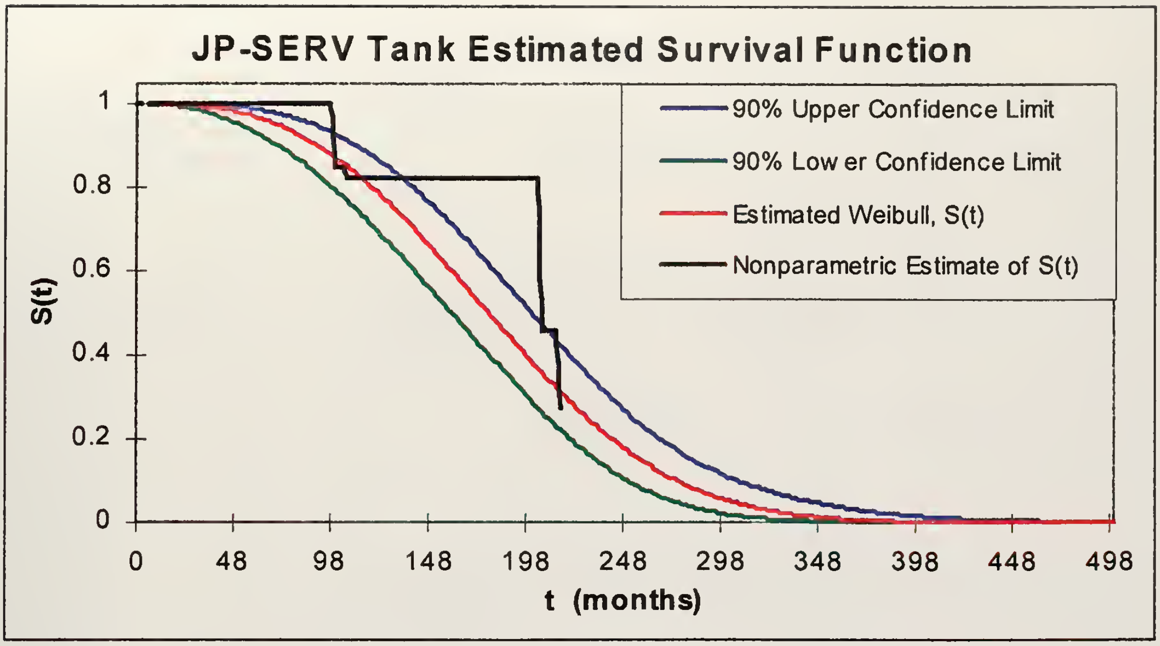


Figure D-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for JP-SERV Group tanks compared to the nonparametric survival distribution.

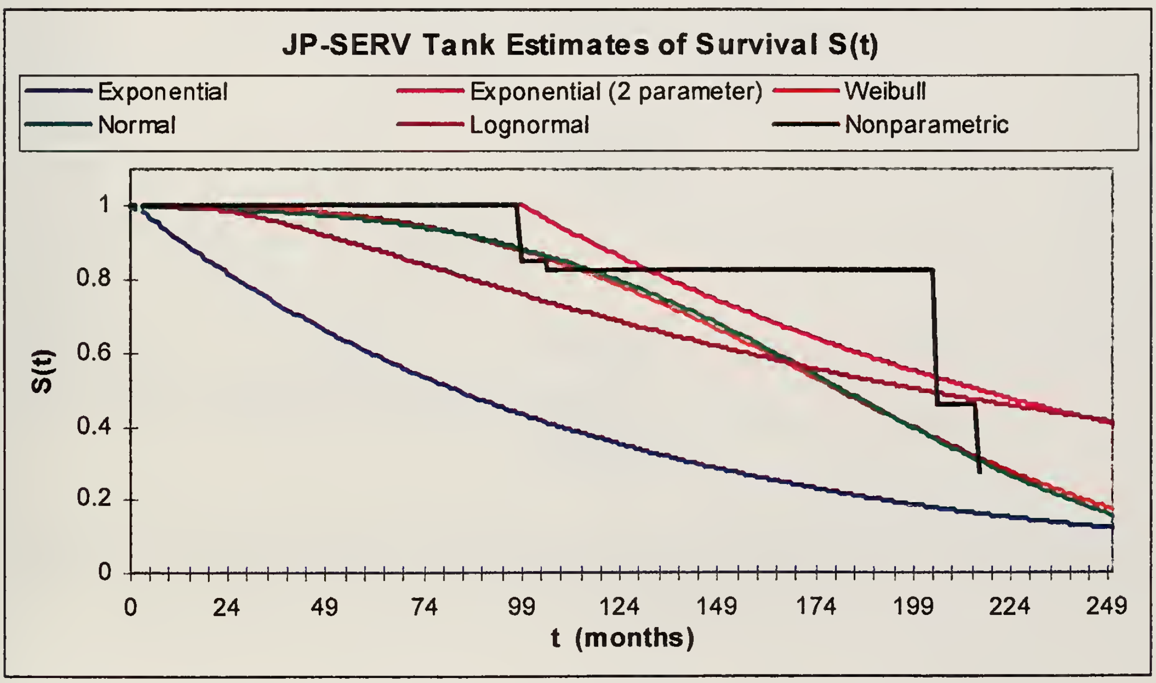


Figure D-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for JP-SERV Group tanks.

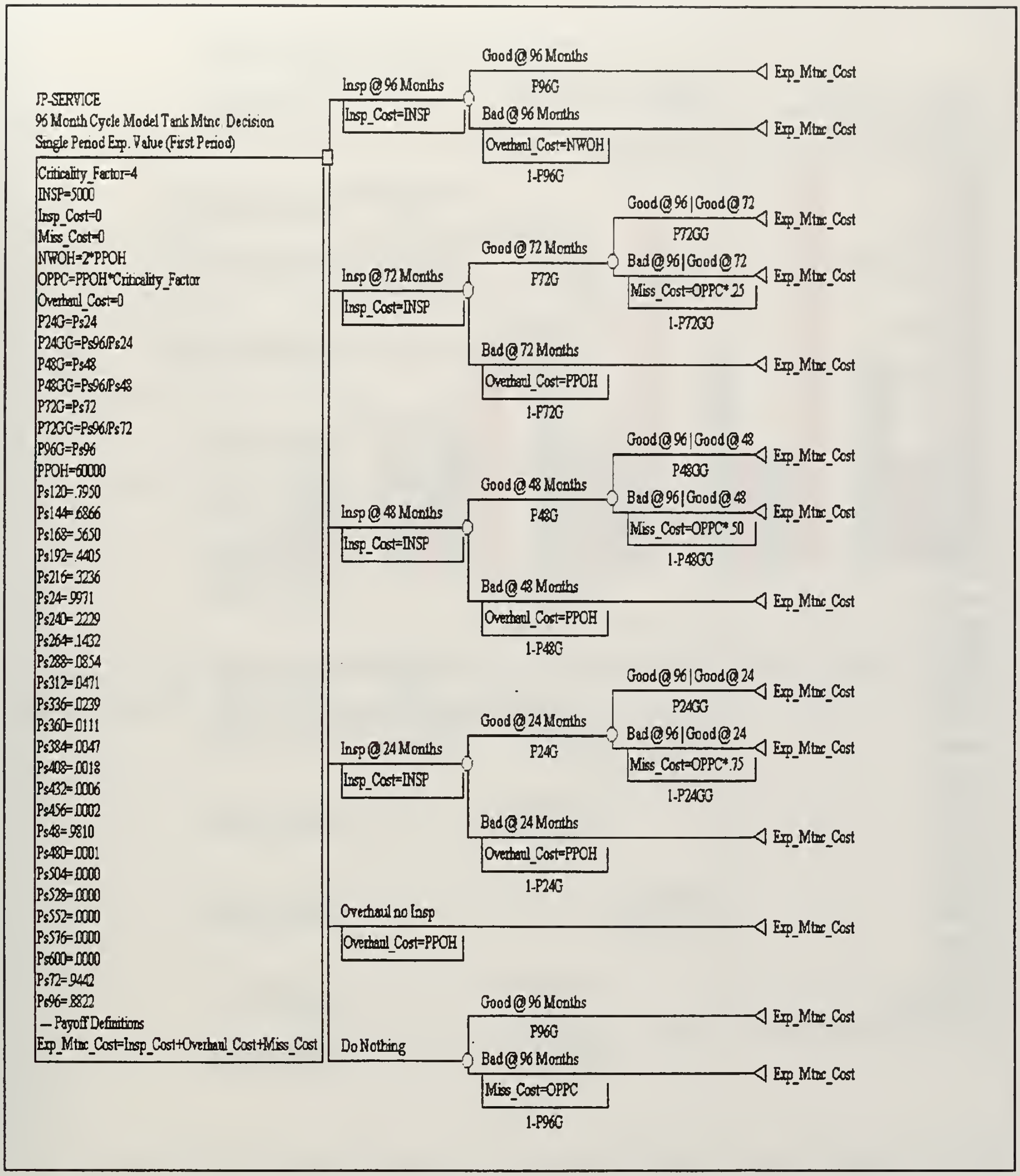


Figure D-7 96 month JP-SERV Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

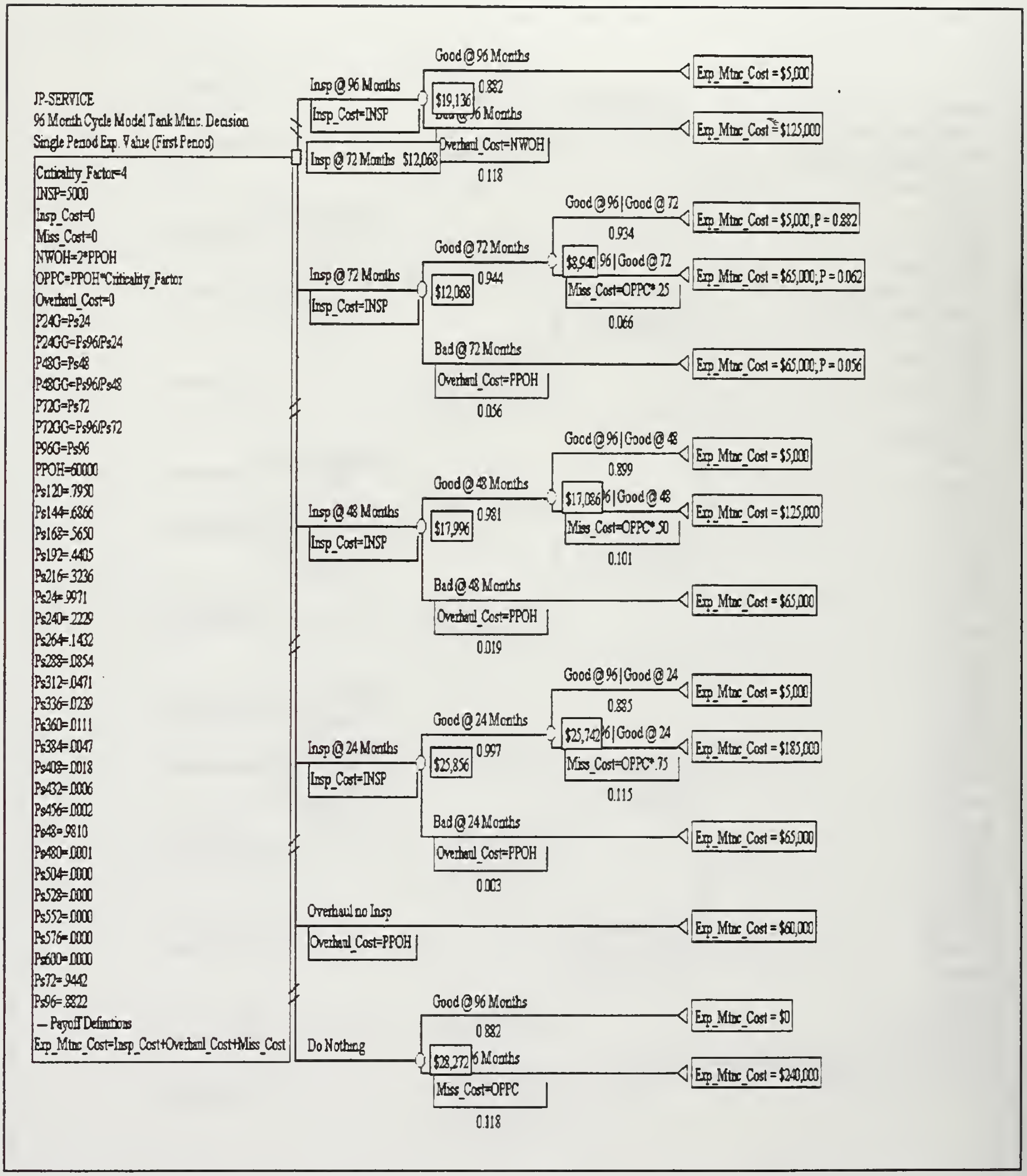


Figure D-8 Roll-back of JP-SERV Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

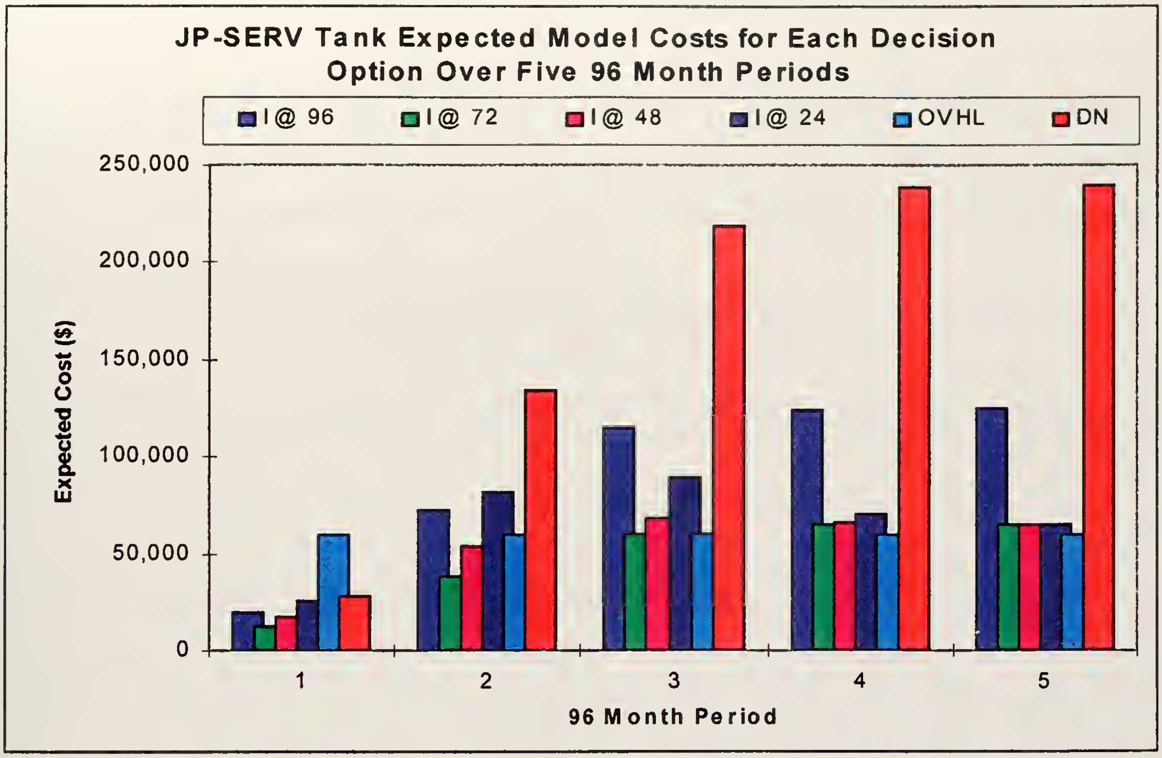


Figure D-9 Expected Model costs for various JP-SERV Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX E . J (TRANS) GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for J(TRANS) group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY J (TRANS) GROUP, CVN 69					
DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
COST	12	IOH:	7	4	3
		ICO:	5	2	1
		NICO:	0	1	1
JP COST & DEFUEL	4	IOH:	3	3	1
		ICO:	1	0	0
		NICO:	0	0	0
SUMP	2	IOH:	2	0	0
		ICO:	0	0	0
		NICO:	0	2	0
COMBINED	30	IOH:	12	7	4
		ICO:	6	2	1
		NICO:	0	3	1
% FAIL			66.67	77.78	80.00
CUM % FAIL			66.67	77.78	93.33
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				27	5
# FAILED				19	4
% (OF INSPECTED) FAILED				70.37	80.00
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure E-1 Summary of J(TRANS) Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
J (TRANS) GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
COST	14	IOH	0	0	1
		ICO	0	1	1
		NICO	14	13	12
JP COST & DEFUEL	4	IOH	0	0	1
		ICO	0	0	1
		NICO	4	4	2
SUMP	2	IOH	0	0	0
		ICO	0	0	2
		NICO	2	2	0
COMBINED	20	IOH	0	0	2
		ICO	0	1	4
		NICO	20	19	14
% FAIL			0.00	0.00	33.33
CUM % FAIL			0.00	0.00	33.33

TANK COATING FAILURE SUMMARY

	SRA '89	SRA '91	SRA '95
COATING AGE (MONTHS)	~34	~61	~112
# INSPECTED	0	1	6
# FAILED	0	0	2
% (OF INSPECTED) FAILED	0.00	0.00	33.33

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure E-2 Summary of J(TRANS) Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
J (TRANS) GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
COST	11	IOH	0
		ICO	4
		NICO	7
JP COST & DEFUEL	5	IOH	0
		ICO	3
		NICO	2
SUMP	2	IOH	0
		ICO	0
		NICO	2
COMBINED	30	IOH	0
		ICO	7
		NICO	11
% FAIL			0
CUM % FAIL			0

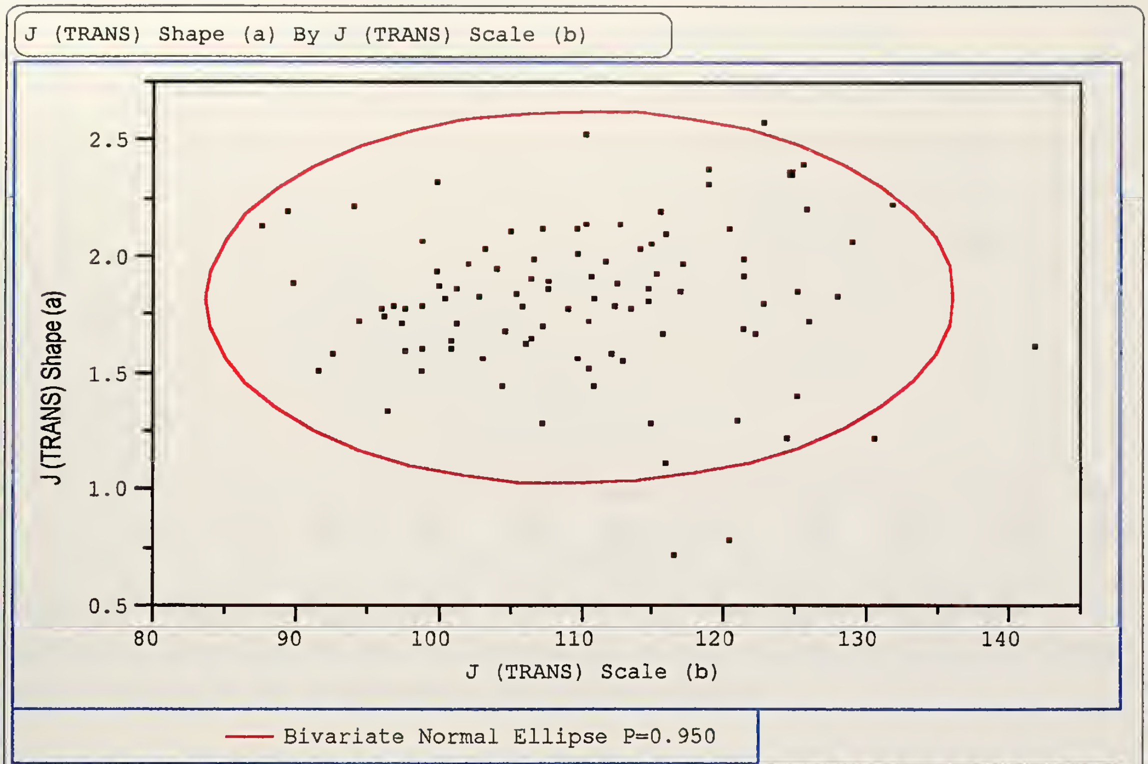
TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	7
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure E-3 Summary of J(TRANS) Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
J (TRANS) Scale (b)	110.14	10.71	0.01	0.9	100
J (TRANS) Shape (a)	1.8289	0.328			

Figure E-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the J(TRANS) group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

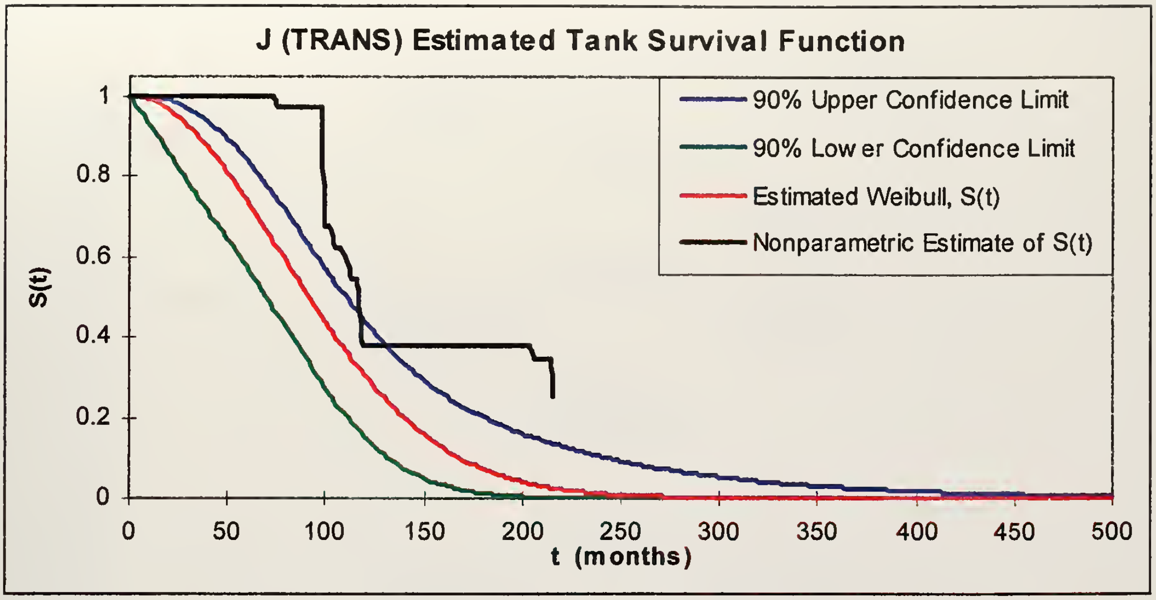


Figure E-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for J(TRANS) Group tanks compared to the nonparametric survival distribution.

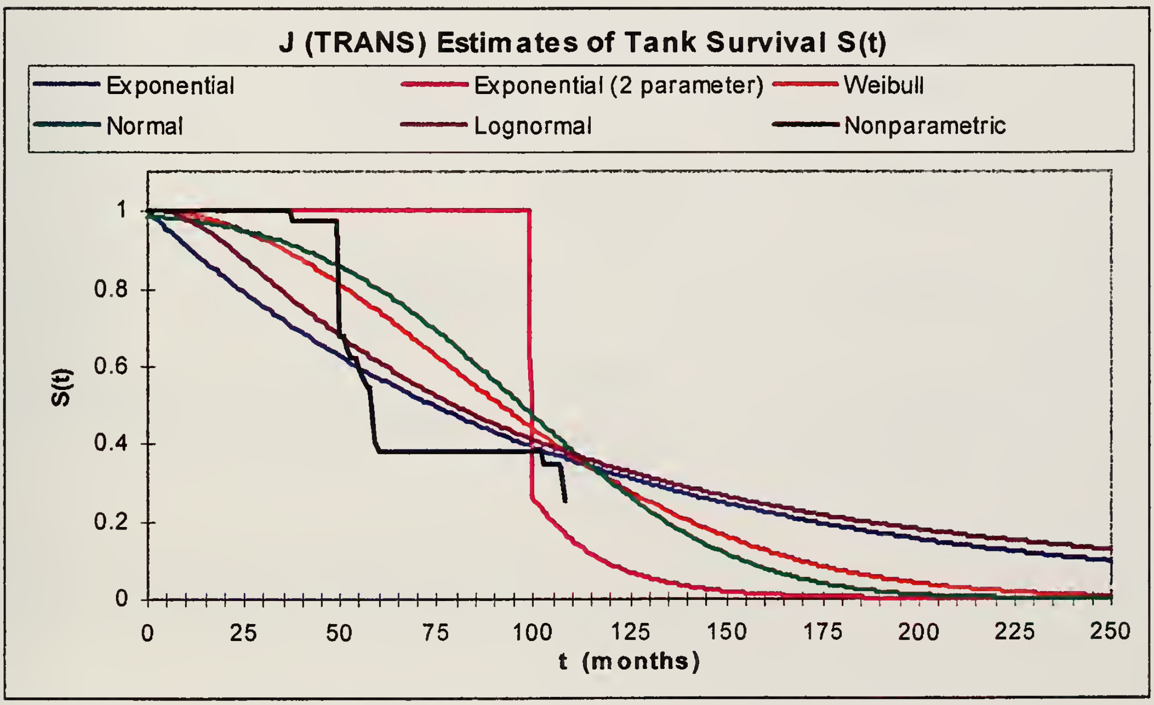


Figure E-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for J(TRANS) Group tanks.

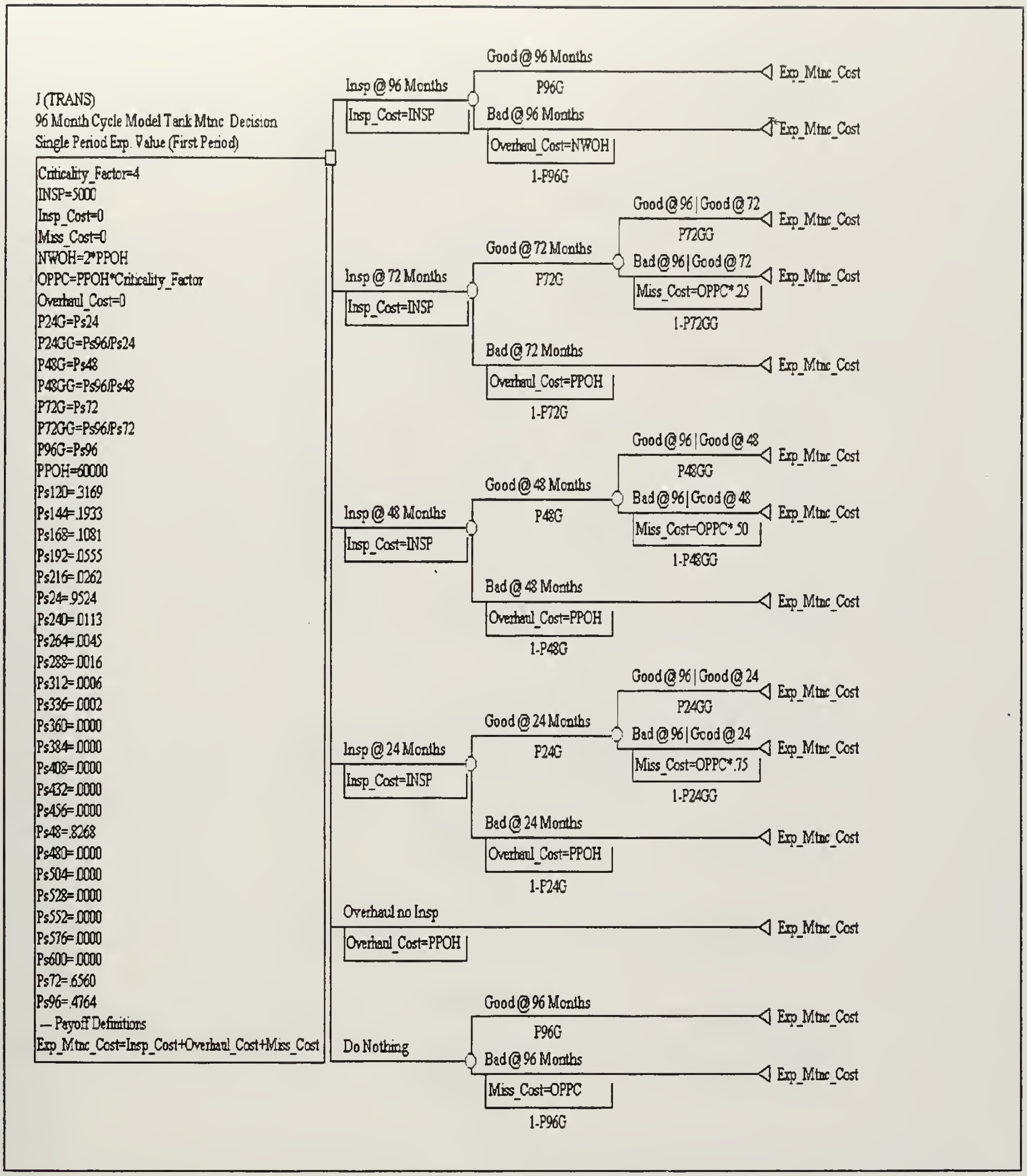


Figure E-7 96 month J(TRANS) Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

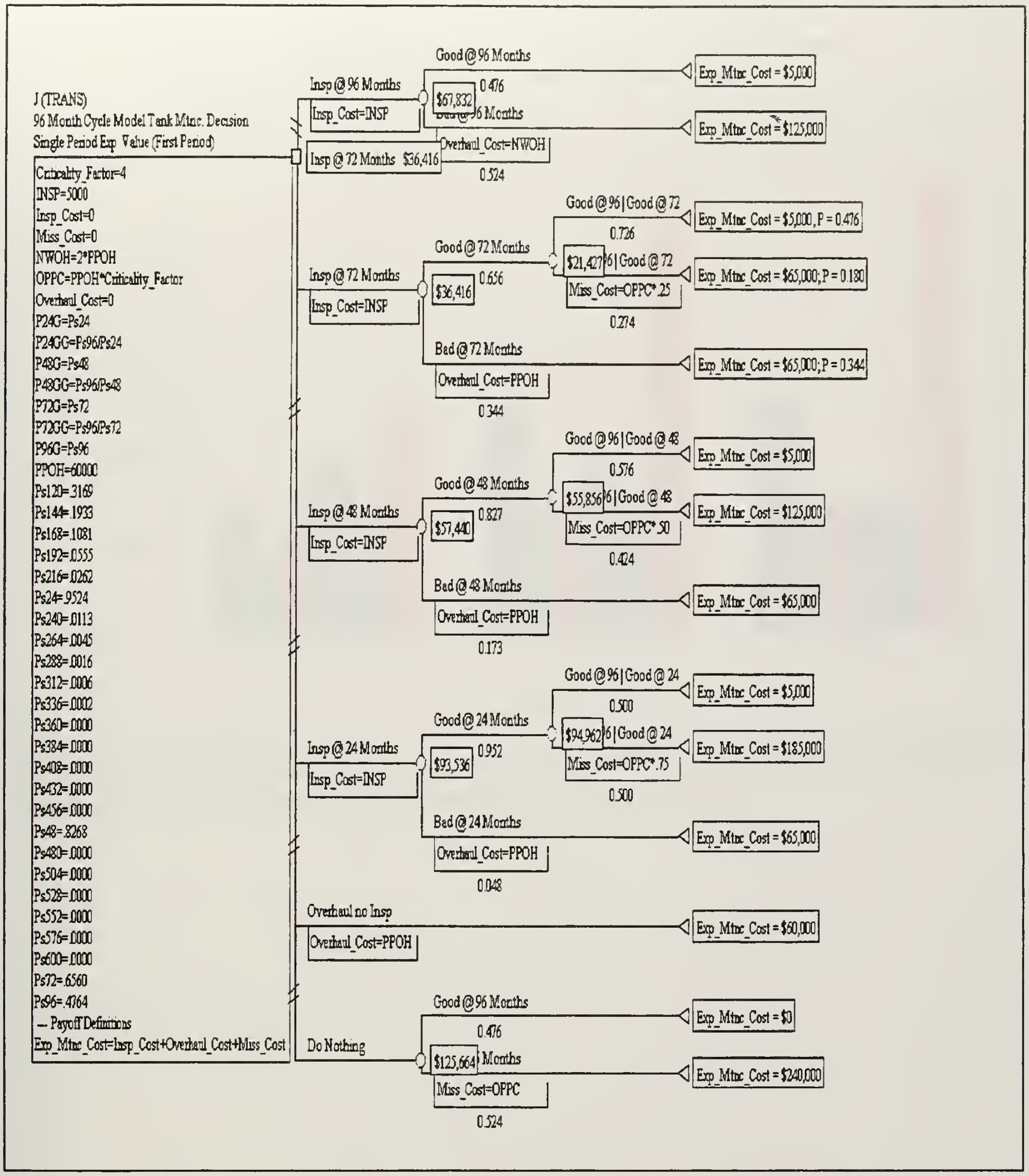


Figure E-8 Roll-back of J(TRANS) Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

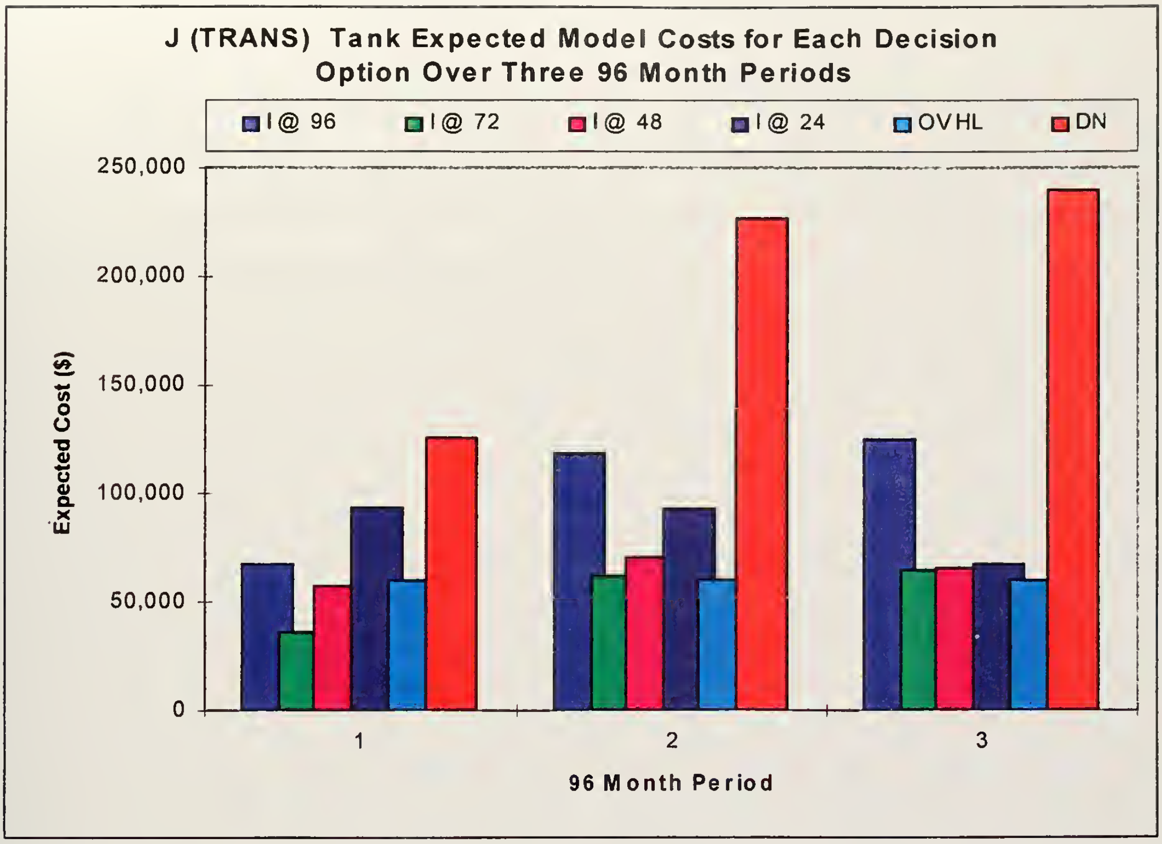


Figure E-9 Expected Model costs for various J(TRANS) Group tank inspection decision options over the first three 96 month periods of tank coating life.

APPENDIX F. J (FULL) GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for J(FULL) Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY J (FULL) GROUP, CVN 69					
DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
JB	52	IOH:	26	17	19
		ICO:	24	7	5
		NICO:	2	2	2
JB NSFO	2	IOH:	2	2	0
		ICO:	0	0	0
		NICO:	0	0	0
JO	3	IOH:	0	0	0
		ICO:	0	0	3
		NICO:	3	0	0
JOB	30	IOH:	20	11	6
		ICO:	8	5	1
		NICO:	2	4	3
JOB NSFO	6	IOH:	6	3	0
		ICO:	0	2	0
		NICO:	0	1	0
JP	58	IOH:	32	16	18
		ICO:	22	12	7
		NICO:	4	4	1
JP NSFO	16	IOH:	16	6	0
		ICO:	0	10	0
		NICO:	0	0	0
COMBINED	167	IOH:	102	55	43
		ICO:	54	36	16
		NICO:	11	11	6
% FAIL			65.38	60.44	72.88
CUM % FAIL			65.38	60.44	90.61
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				247	59
# FAILED				157	43
% OF INSP. FAILED				63.56	72.88
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure F-1 Summary of J(FULL) Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
J (FULL) GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
JB	59	IOH	0	0	0
		ICO	1	4	2
		NICO	58	54	56
JB NSFO	2	IOH	0	0	0
		ICO	0	0	0
		NICO	2	2	2
JO	3	IOH	0	0	0
		ICO	0	0	0
		NICO	3	3	3
JOB	30	IOH	0	0	0
		ICO	0	5	2
		NICO	30	25	28
JOB NSFO	6	IOH	0	0	0
		ICO	0	0	0
		NICO	6	6	6
JP	56	IOH	0	0	0
		ICO	0	8	2
		NICO	56	48	54
JP NSFO	16	IOH	0	0	0
		ICO	0	0	0
		NICO	16	16	16
COMBINED	172	IOH	0	0	0
		ICO	1	17	6
		NICO	171	154	165
% FAIL			0.00	0.00	0.00
CUM % FAIL			0.00	0.00	0.00

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~34	~61	~112
# INSPECTED	1	17	6
# FAILED	0	0	0
% (OF INSPECTED) FAILED	0.00	0.00	0.00

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure F-2 Summary of J(FULL) Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
J (FULL) GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
JB	52	IOH	0
		ICO	19
		NICO	33
JB NSFO	2	IOH	0
		ICO	0
		NICO	2
JO	3	IOH	0
		ICO	0
		NICO	3
JOB	30	IOH	0
		ICO	11
		NICO	19
JOB NSFO	6	IOH	0
		ICO	0
		NICO	6
JP	58	IOH	0
		ICO	18
		NICO	40
JP NSFO	16	IOH	0
		ICO	0
		NICO	16
COMBINED	167	IOH	0
		ICO	48
		NICO	119
% FAIL			0
CUM % FAIL			0

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	48
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure F-3 Summary of J(FULL) Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).

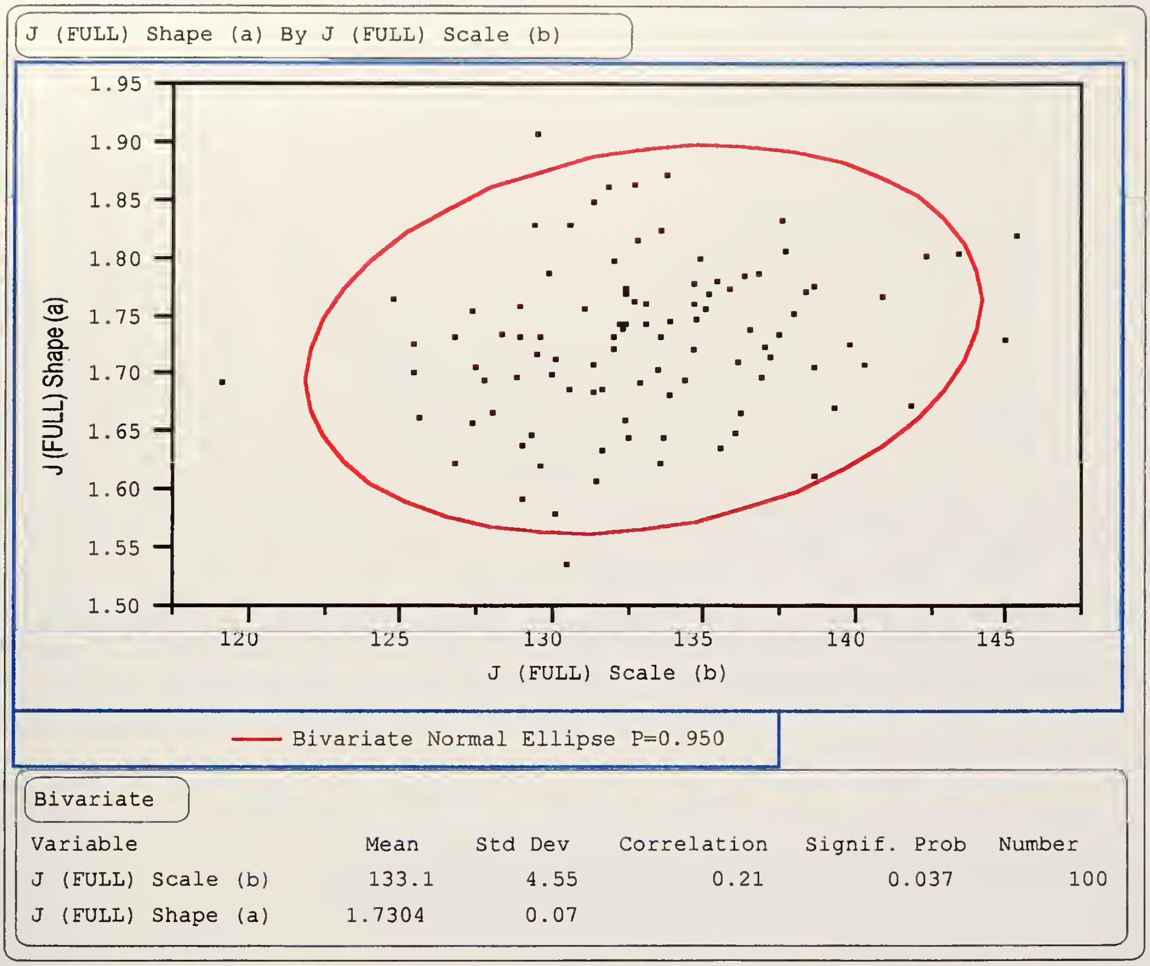


Figure F-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the J(FULL) group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

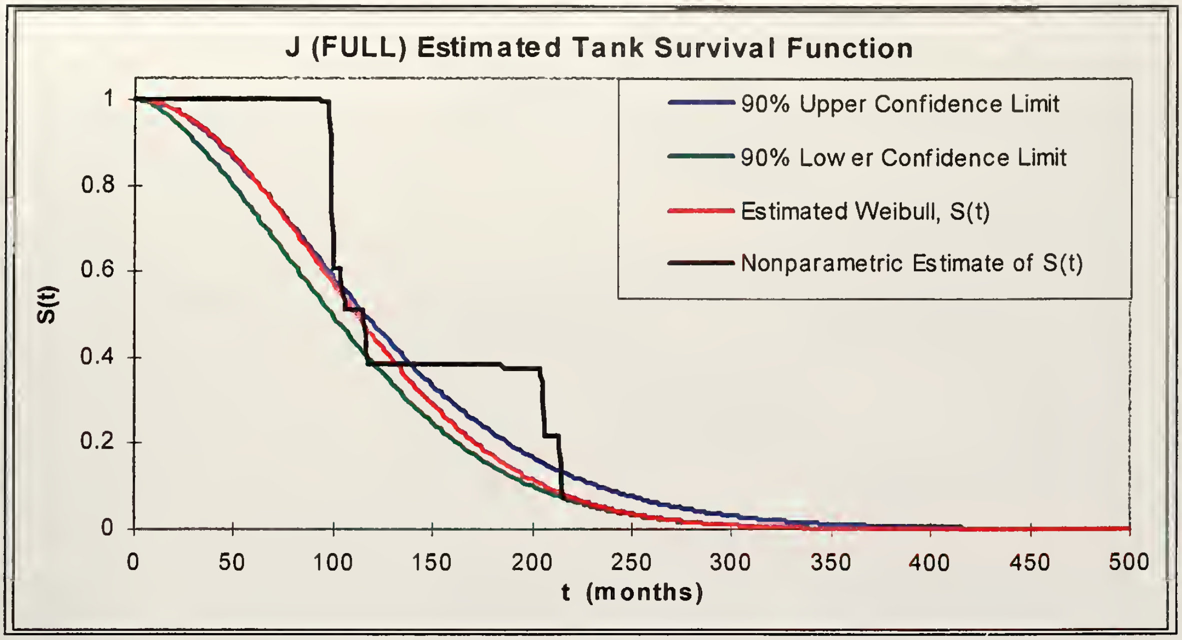


Figure F-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for J(FULL) Group tanks compared to the nonparametric survival distribution.

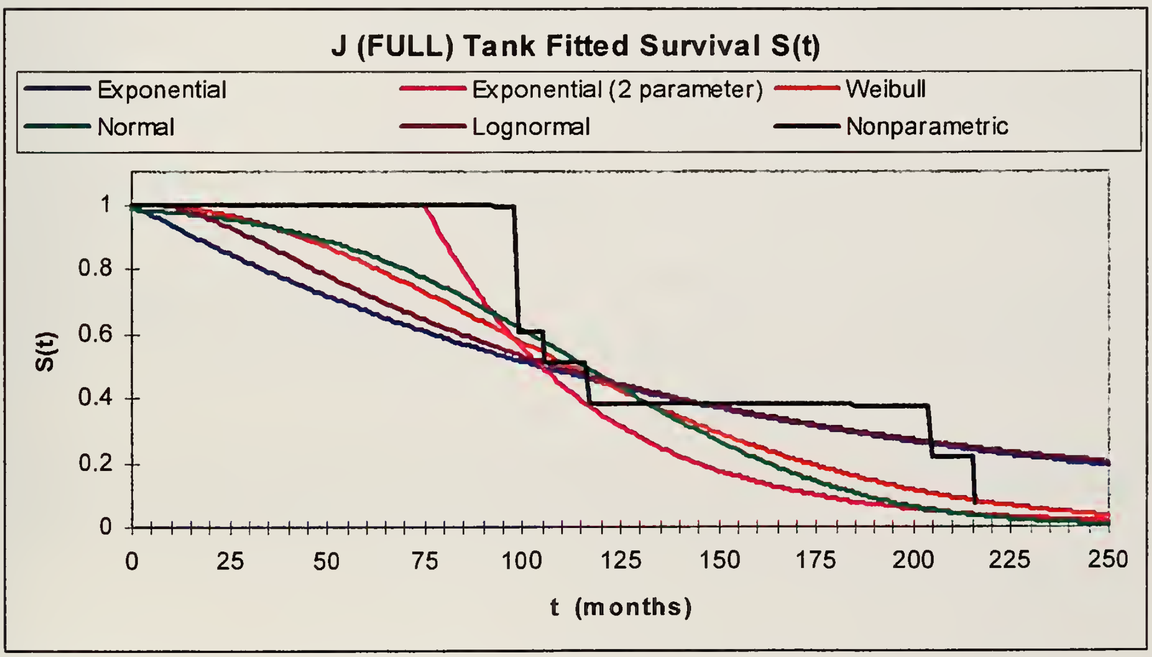


Figure F-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for J(FULL) Group tanks.

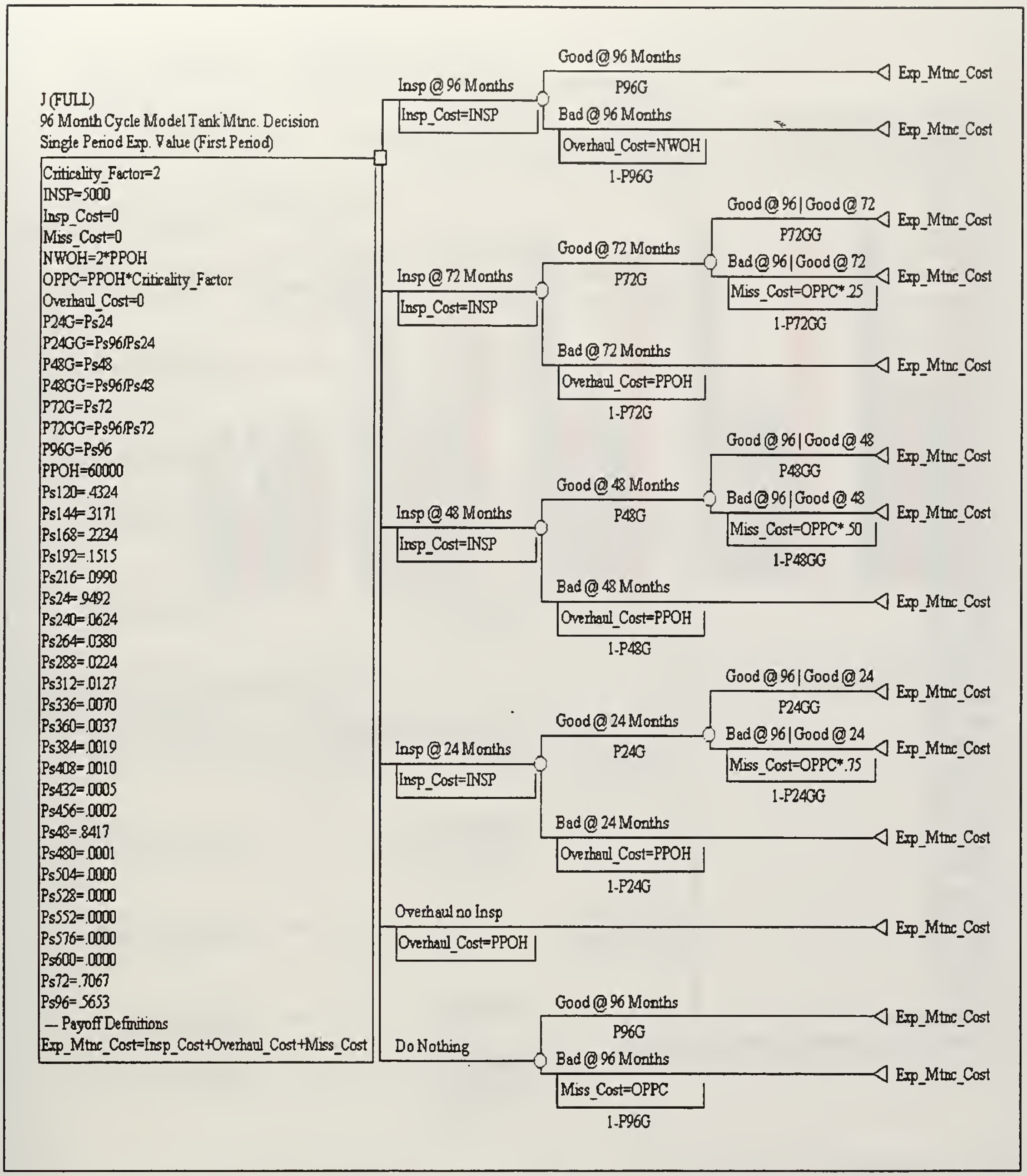


Figure F-7 96 month J(FULL) Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

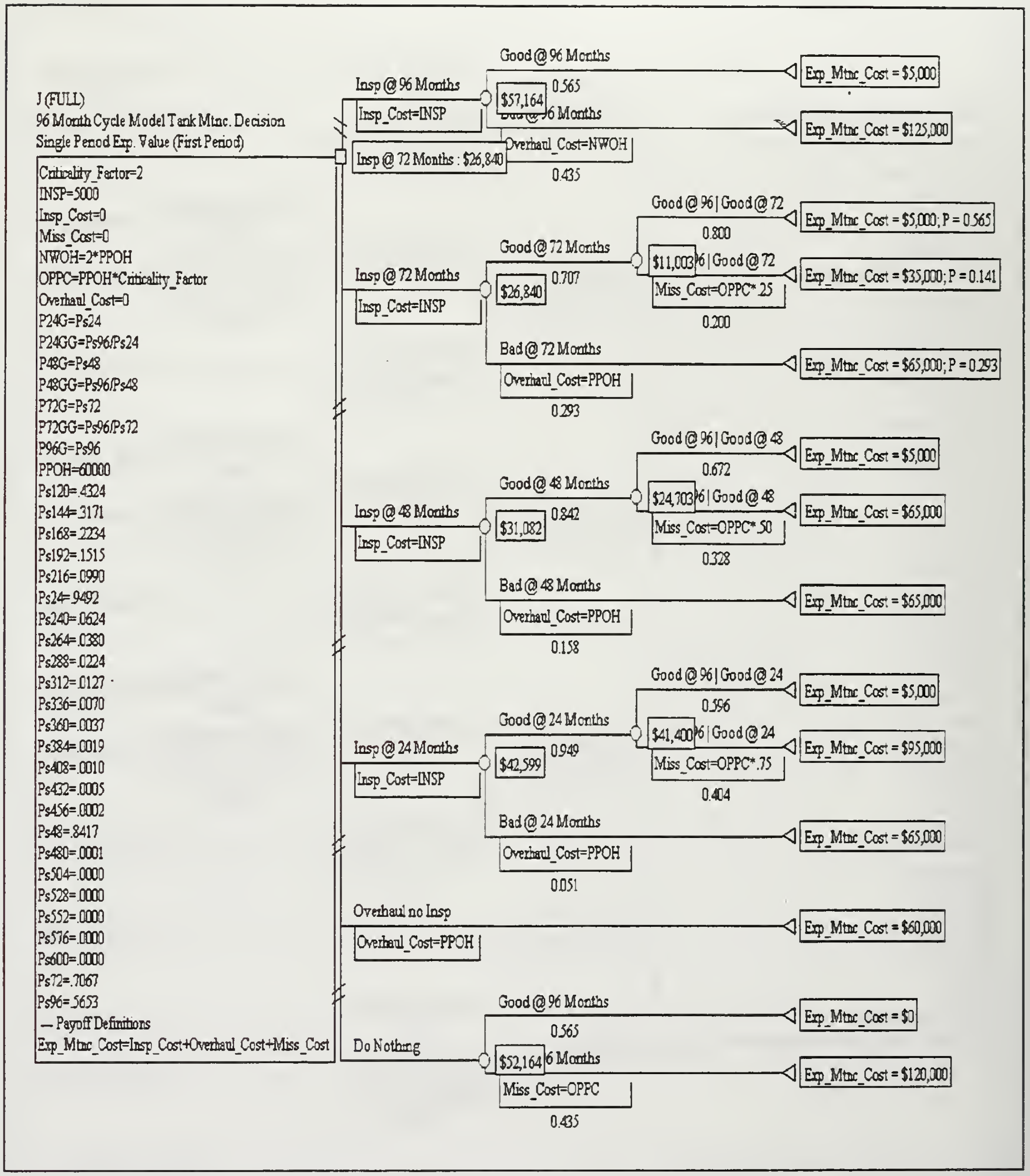


Figure F-8 Roll-back of J(FULL) Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

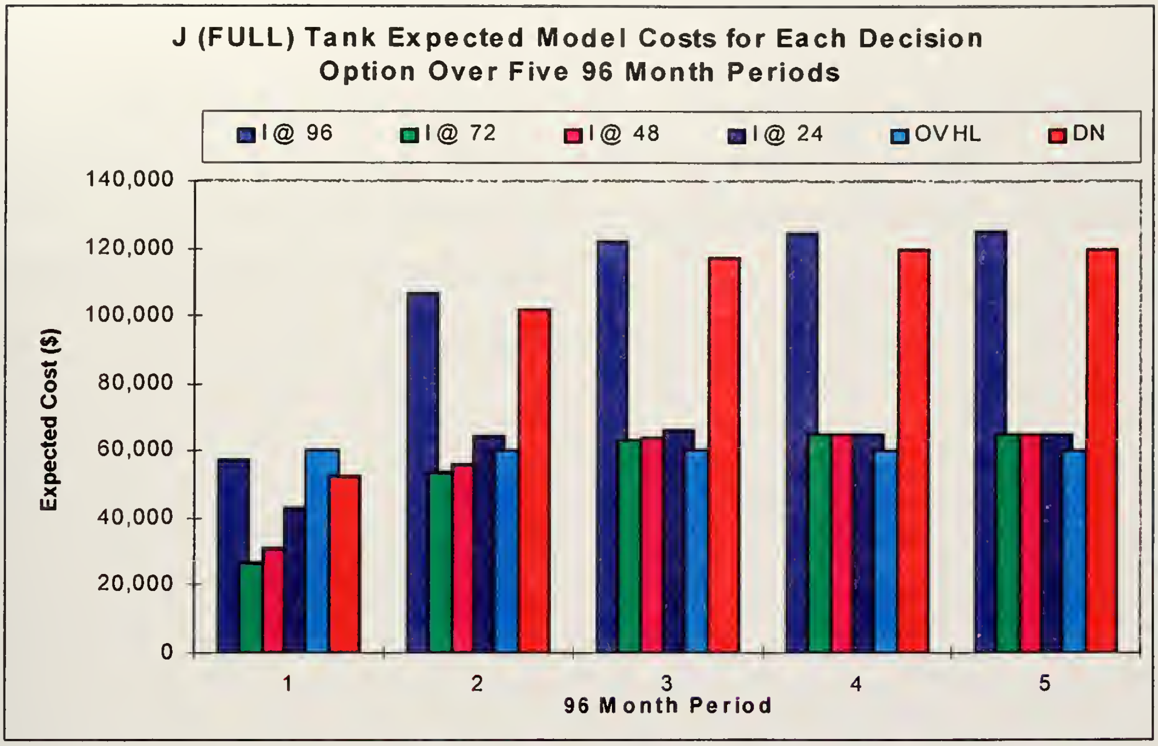


Figure F-9 Expected Model costs for various J(FULL) Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX G. LUBE OIL GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for J(FULL) Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY
LUBE-OIL GROUP, CVN 69

DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
AUX-LO-SET	3	IOH:	0	0	0
		ICO:	1	0	0
		NICO:	2	0	3
AUX-LO-STOW	4	IOH:	0	0	0
		ICO:	0	0	0
		NICO:	4	0	4
LO	3	IOH:	0	0	0
		ICO:	0	0	3
		NICO:	3	0	0
LO SET	15	IOH:	0	0	0
		ICO:	0	0	15
		NICO:	15	0	0
LO STOW	28	IOH:	0	0	0
		ICO:	0	0	22
		NICO:	28	0	6
COMBINED	53	IOH:	0	0	0
		ICO:	1	0	40
		NICO:	52	0	13
% FAIL			0	0	0
CUM % FAIL			0	0	0

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~105	~210
# INSPECTED	1	40
# FAILED	0	0
% OF INSP. FAILED	0	0

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure G-1 Summary of LUBE-OIL Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY LUBE-OIL GROUP, CVN 71					
DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
AUX-LO-SET	3	IOH	0	0	0
		ICO	0	0	0
		NICO	3	3	3
AUX-LO-STOW	4	IOH	0	0	0
		ICO	0	0	0
		NICO	4	4	4
LO	3	IOH	0	0	0
		ICO	0	0	0
		NICO	3	3	3
LO SET	15	IOH	0	0	0
		ICO	0	0	2
		NICO	15	15	13
LO STOW	28	IOH	0	0	0
		ICO	0	0	0
		NICO	28	28	28
COMBINED	53	IOH	0	0	0
		ICO	0	0	2
		NICO	53	53	51
% FAIL			0.00	0.00	0.00
CUM % FAIL			0.00	0.00	0.00
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			0	0	2
# FAILED			0	0	0
% (OF INSPECTED) FAILED			0.00	0.00	0.00

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure G-2 Summary of LUBE-OIL Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
LUBE-OIL GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
AUX-LO-SET	3	IOH	0
		ICO	0
		NICO	3
AUX-LO-STOW	4	IOH	0
		ICO	0
		NICO	4
LO	3	IOH	0
		ICO	0
		NICO	3
LO SET	15	IOH	0
		ICO	0
		NICO	15
LO STOW	28	IOH	0
		ICO	0
		NICO	28
COMBINED	53	IOH	0
		ICO	0
		NICO	53
% FAIL			0
CUM % FAIL			0

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	0
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure G-3 Summary of LUBE-OIL Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).

APPENDIX H. SEA WTR (FREQ) GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for SEA WTR (FREQ) Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY SEA WTR (FREQ) GROUP, CVN 69					
DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
VOID LC	10	IOH:	7	6	1
		ICO:	1	0	1
		NICO:	2	1	1
PEAK SWB	2	IOH:	2	2	0
		ICO:	0	0	0
		NICO:	0	0	0
OVERFLOW BOX	11	IOH:	0	0	0
		ICO:	0	0	0
		NICO:	11	0	11
ONBD DISCHG S.	5	IOH:	3	0	0
		ICO:	0	0	0
		NICO:	2	3	2
FRS WTR CLC	3	IOH:	1	1	2
		ICO:	0	0	0
		NICO:	2	0	0
DIRTY DRN CLC	6	IOH:	1	0	0
		ICO:	1	0	1
		NICO:	4	1	3
COMBINED	37	IOH:	14	9	3
		ICO:	2	0	2
		NICO:	21	5	17
% FAIL			87.50	100.00	60.00
CUM % FAIL			87.50	100.00	95.00
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				25	5
# FAILED				23	3
% (OF INSPECTED) FAILED				92.00	60.00
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure H-1 Summary of SEA WTR (FREQ) Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
SEA WTR (FREQ) GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
VOID LC	11	IOH	0	0	0
		ICO	0	3	1
		NICO	11	8	10
PEAK SWB	2	IOH	0	0	0
		ICO	0	0	0
		NICO	2	2	2
OVERFLOW BOX	11	IOH	0	0	1
		ICO	0	0	1
		NICO	11	11	9
ONBD DISCHG S.	5	IOH	0	0	0
		ICO	0	0	0
		NICO	5	5	5
FRS WTR CLC	4	IOH	0	0	0
		ICO	0	0	0
		NICO	4	4	4
DIRTY DRN CLC	6	IOH	0	0	0
		ICO	0	0	0
		NICO	6	6	6
COMBINED	39	IOH	0	0	1
		ICO	0	3	2
		NICO	39	36	36
% FAIL			0.00	0.00	33.33
CUM % FAIL			0.00	0.00	33.33

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~34	~61	~112
# INSPECTED	0	3	3
# FAILED	0	0	1
% (OF INSPECTED) FAILED	0.00	0.00	33.33

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

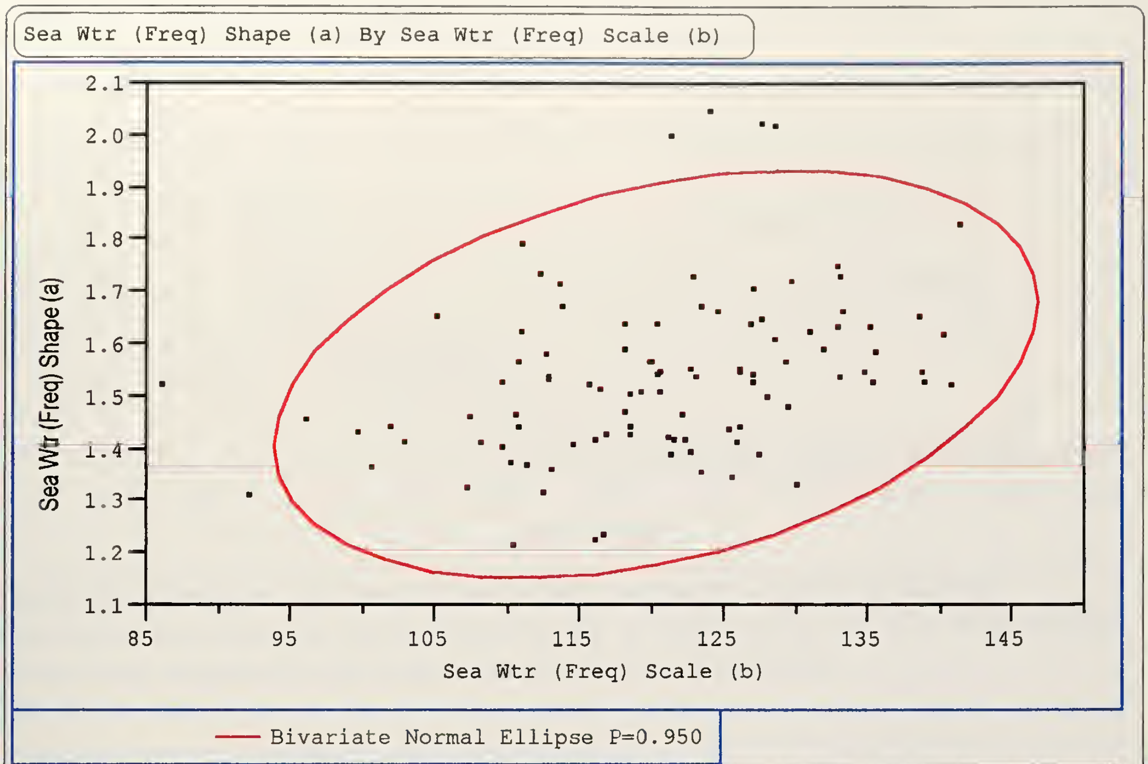
Figure H-2 Summary of SEA WTR (FREQ) Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY SEA WTR (FREQ) GROUP, CVN 72			
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**EDSRA '96 (75 MOS)**
VOID LC	10	IOH	0
		ICO	6
		NICO	4
PEAK SWB	2	IOH	0
		ICO	0
		NICO	2
OVERFLOW BOX	11	IOH	0
		ICO	0
		NICO	11
ONBD DISCHG S.	5	IOH	0
		ICO	0
		NICO	5
FRS WTR CLC	4	IOH	0
		ICO	0
		NICO	4
DIRTY DRN CLC	6	IOH	0
		ICO	0
		NICO	6
COMBINED	38	IOH	0
		ICO	6
		NICO	32
% FAIL			0
CUM % FAIL			0

TANK COATING FAILURE SUMMARY	
COATING AGE (MONTHS)	~75
# INSPECTED	6
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY	
IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure H-3 Summary of SEA WTR (FREQ) Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
Sea Wtr (Freq) Scale (b)	120.49	10.84	0.36	0.0003	100
Sea Wtr (Freq) Shape (a)	1.5489	0.1602			

Figure H-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the SEA WTR (FREQ) group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

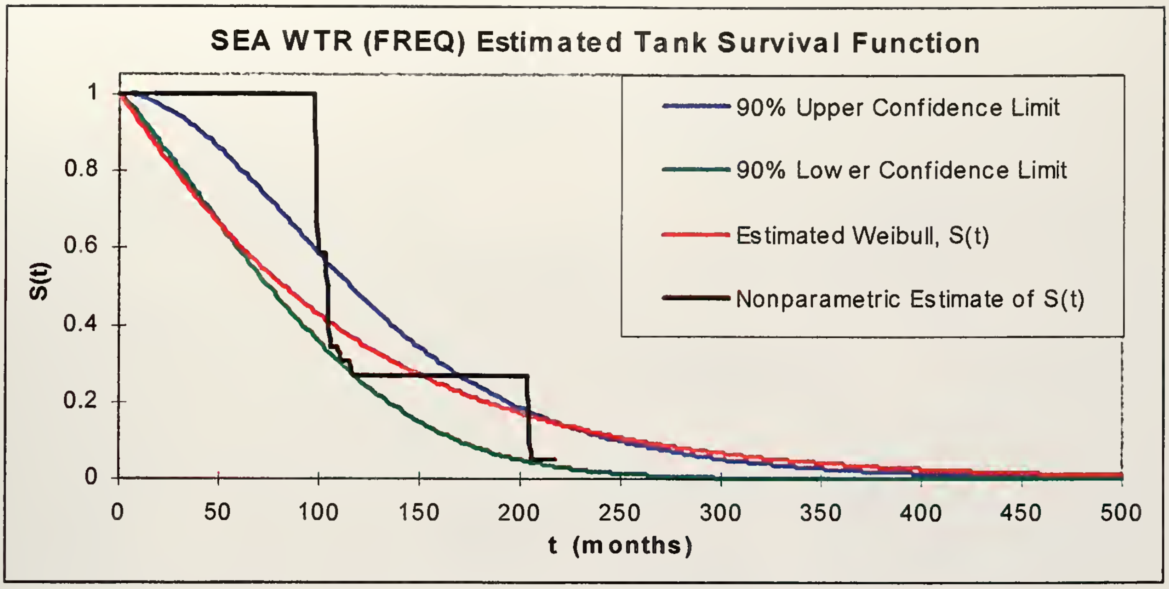


Figure H-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for SEA WTR (FREQ) Group tanks compared to the nonparametric survival distribution.

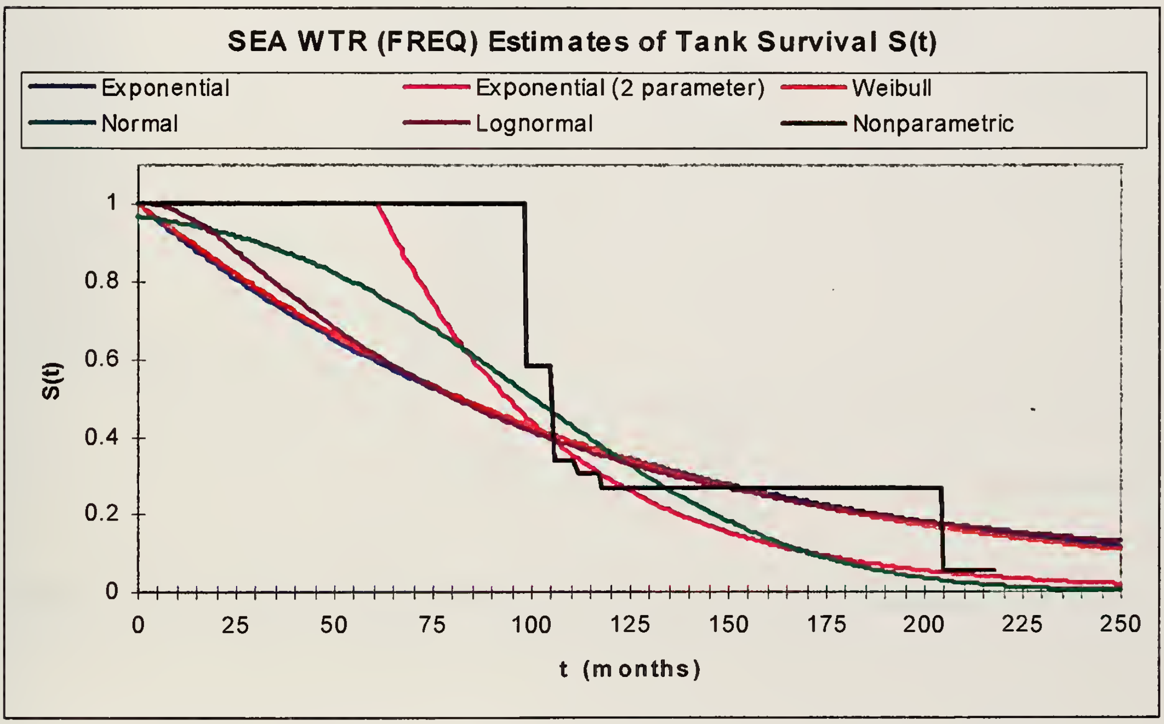


Figure H-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for SEA WTR (FREQ) Group tanks.

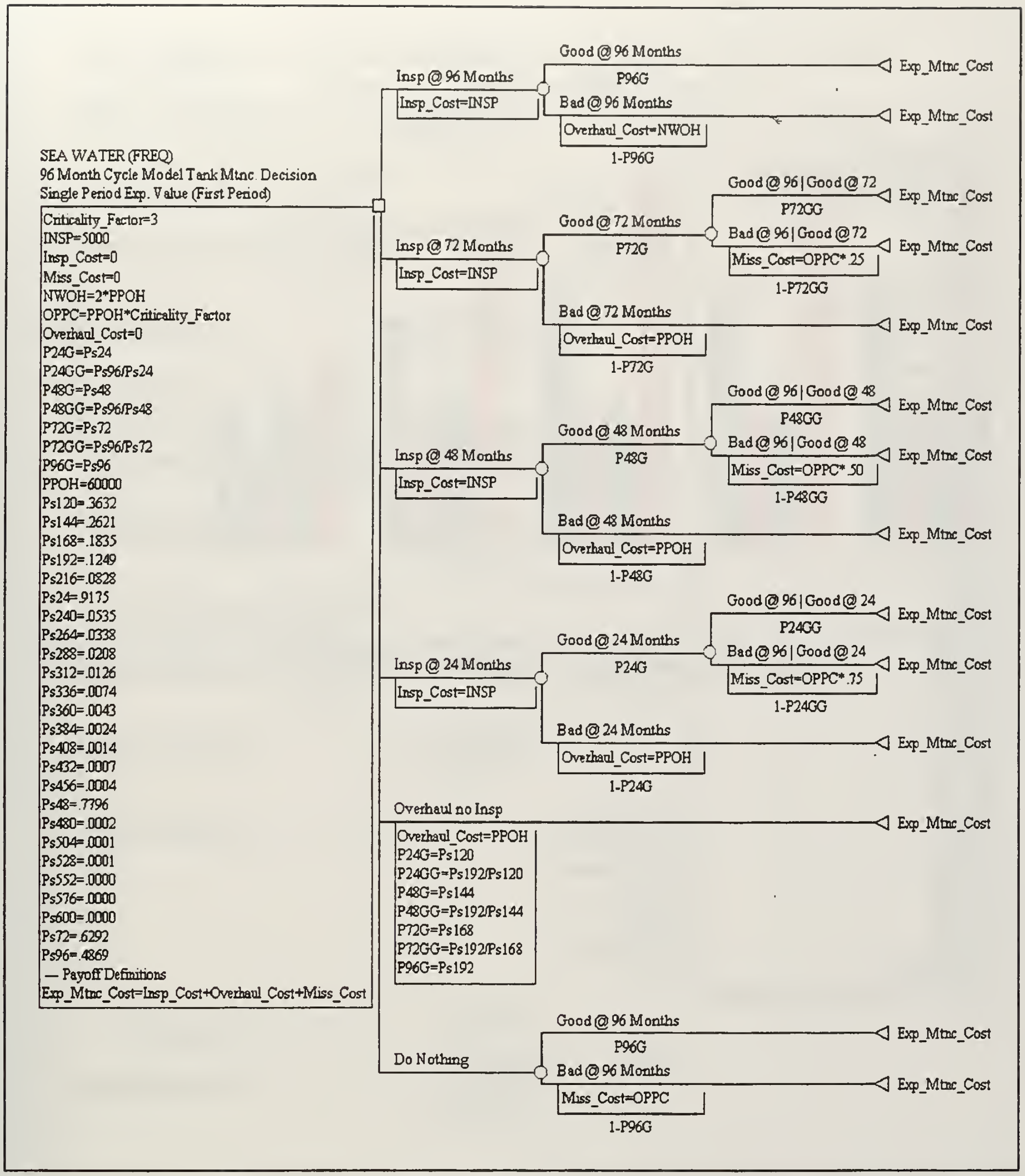


Figure H-7 96 month SEA WTR (FREQ) Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

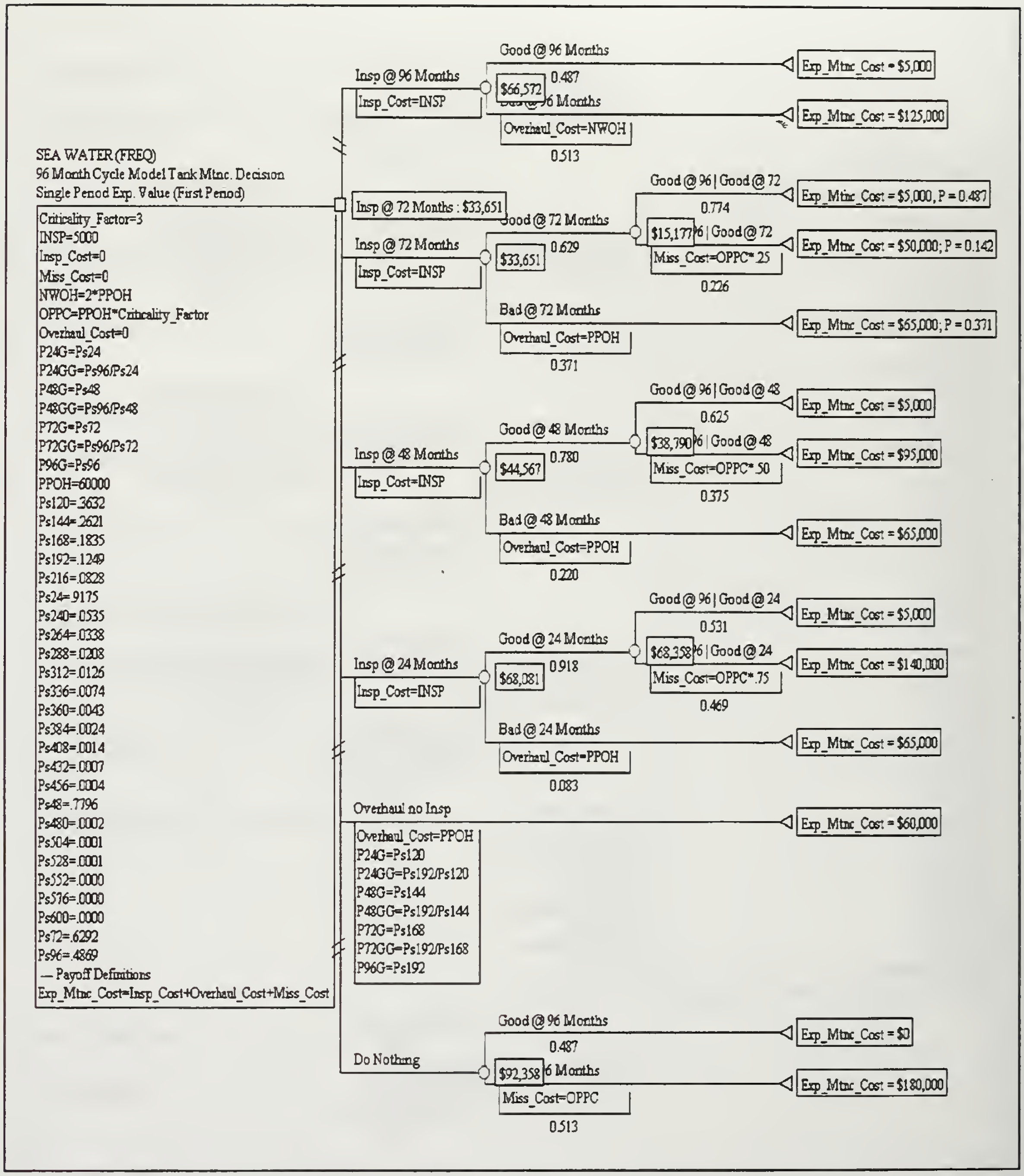


Figure H-8 Roll-back of SEA WTR (FREQ) Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

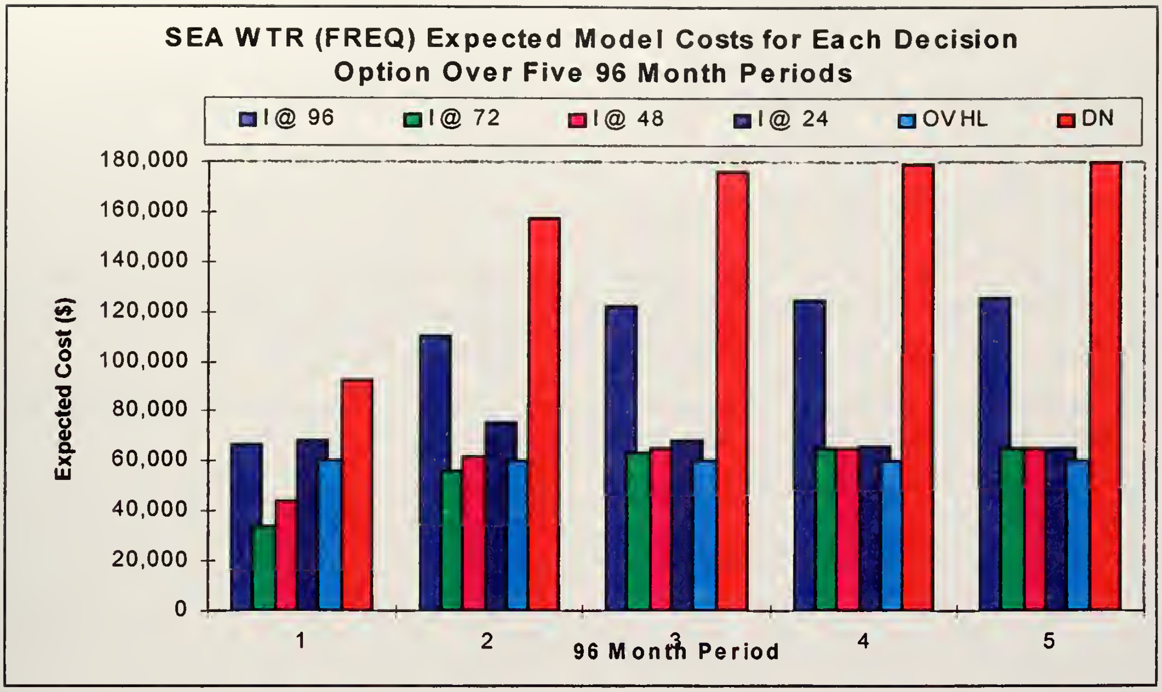


Figure H-9 Expected Model costs for various SEA WTR (FREQ) Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX I. SEA WTR (INF) GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for SEA WTR (INF) Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY
SEA WTR (INF) GROUP, CVN 69

DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
DC	27	IOH:	3	2	5
		ICO:	13	1	9
		NICO:	11	0	4
VOID DC	57	IOH:	15	3	7
		ICO:	36	2	9
		NICO:	6	10	26
COMBINED	84	IOH:	18	5	12
		ICO:	49	3	18
		NICO:	17	10	30
% FAIL			26.87	62.50	40.00
CUM % FAIL			26.87	62.50	56.12

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~105	~210
# INSPECTED	75	30
# FAILED	23	12
% (OF INSPECTED) FAILED	30.67	40.00

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure I-1 Summary of SEA WTR (INF) Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
SEA WTR (INF) GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
DC	27	IOH	0	1	1
		ICO	0	1	1
		NICO	27	25	25
VOID DC	57	IOH	0	2	12
		ICO	0	7	0
		NICO	57	48	45
COMBINED	84	IOH	0	3	13
		ICO	0	8	1
		NICO	84	73	70
% FAIL			0.00	27.27	92.86
CUM % FAIL			0.00	27.27	92.86
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			0	11	14
# FAILED			0	3	13
% (OF INSPECTED) FAILED			0.00	27.27	92.86

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure I-2 Summary of SEA WTR (INF) Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
SEA WTR (INF) GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
DC	27	IOH	3
		ICO	6
		NICO	18
VOID DC	57	IOH	20
		ICO	33
		NICO	4
COMBINED	84	IOH	23
		ICO	39
		NICO	22
% FAIL			37.10
CUM % FAIL			37.10

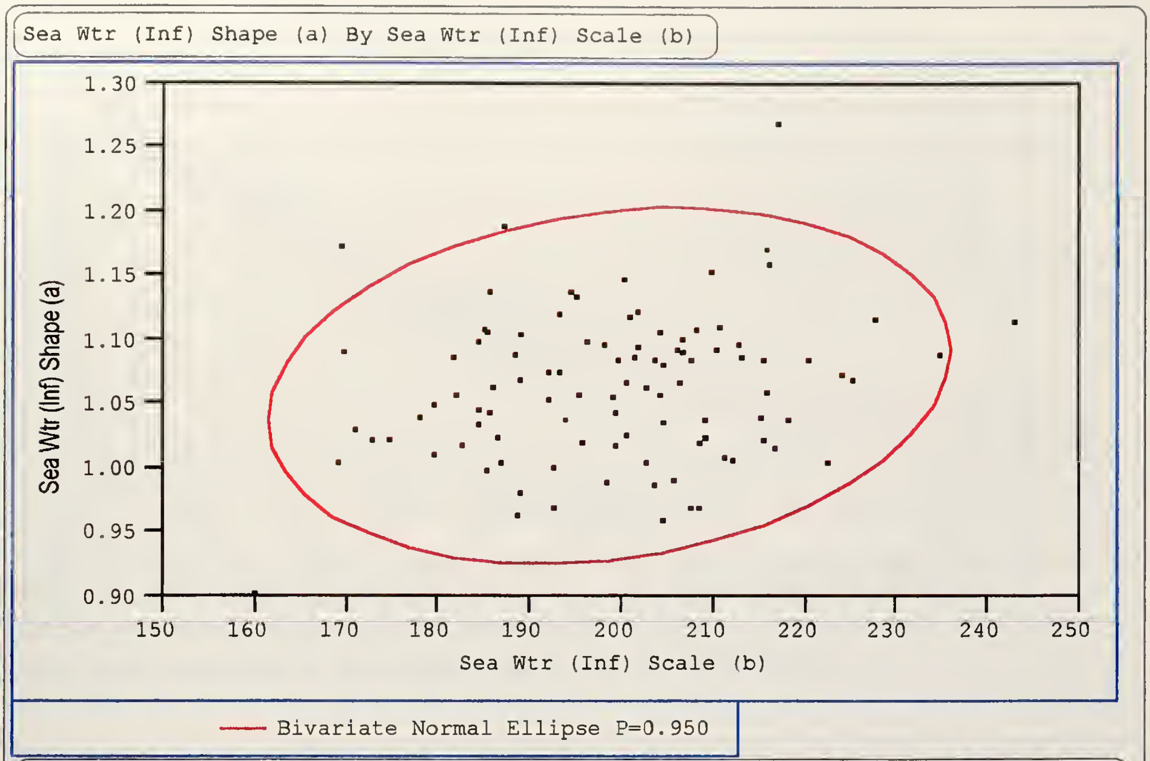
TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	62
# FAILED	23
% (OF INSPECTED) FAILED	37.10

INSPECTION CODE KEY

IOH	= INSPECTED AND OVERHAULED
ICO	= INSPECTED AND NOT OVERHAULED
NICO	= NOT INSPECTED AND NOT OVERHAULED

Figure I-3 Summary of SEA WTR (INF) Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
Sea Wtr (Inf) Scale (b)	198.89	15.186	0.2	0.05	100
Sea Wtr (Inf) Shape (a)	1.0652	0.0568			

Figure I-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the SEA WTR (INF) group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

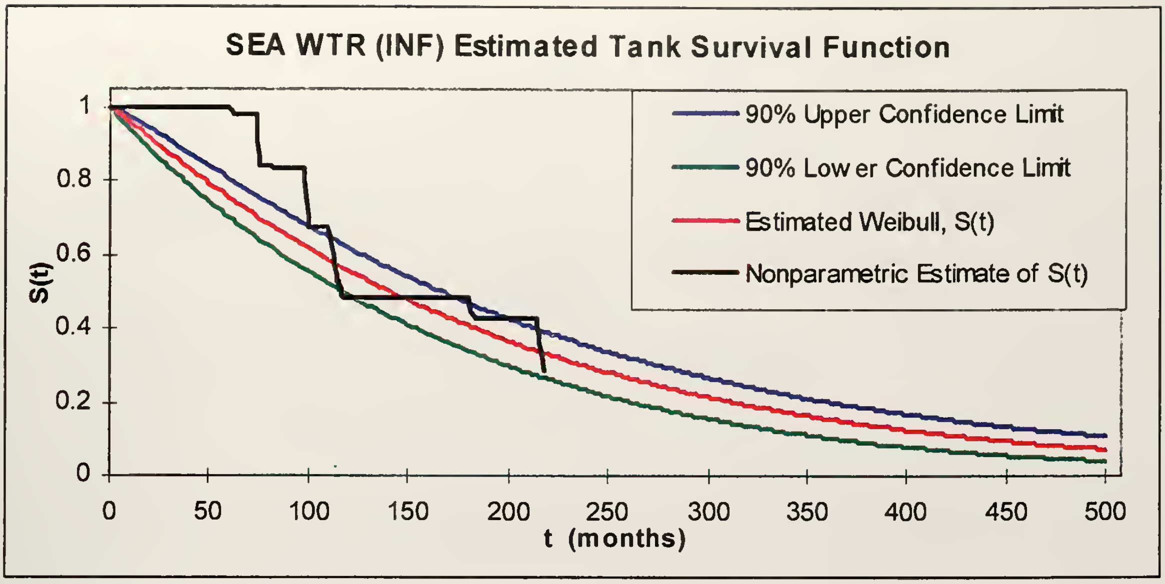


Figure I-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for SEA WTR (INF) Group tanks compared to the nonparametric survival distribution.

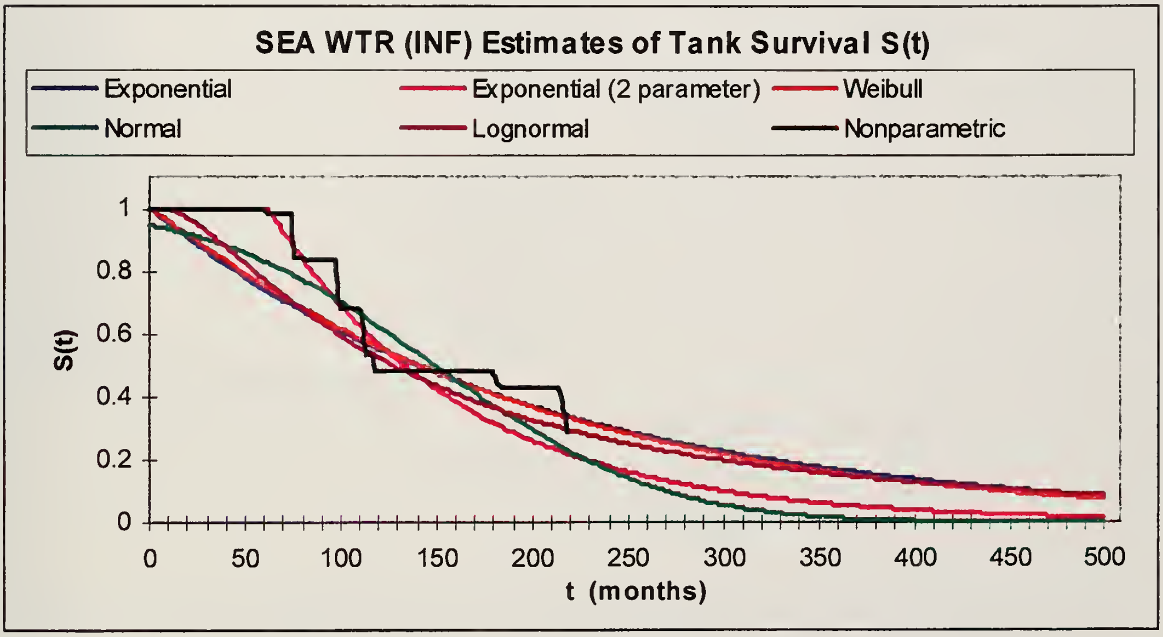


Figure I-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for SEA WTR (INF) Group tanks.

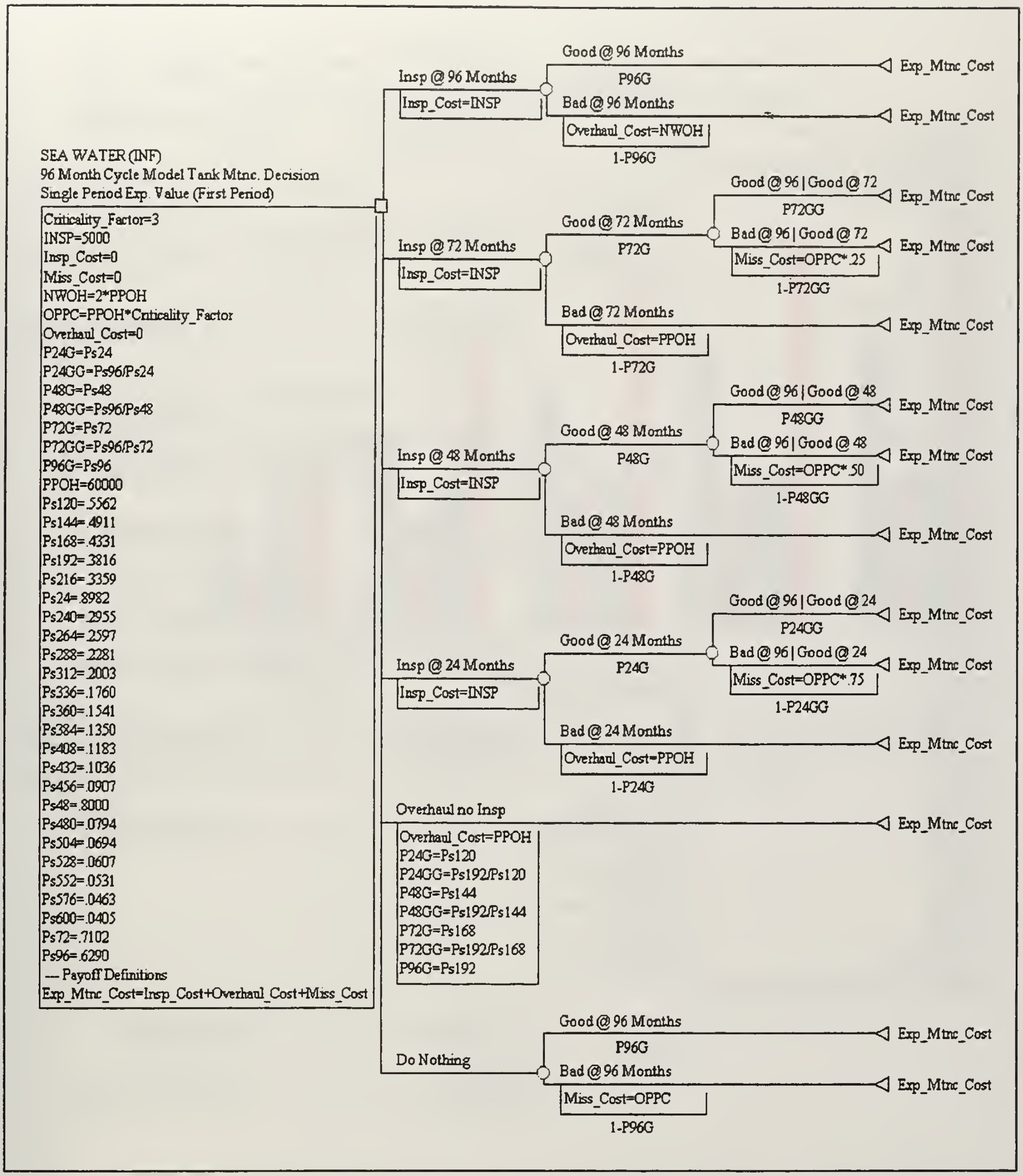


Figure I-7 96 month SEA WTR (INF) Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

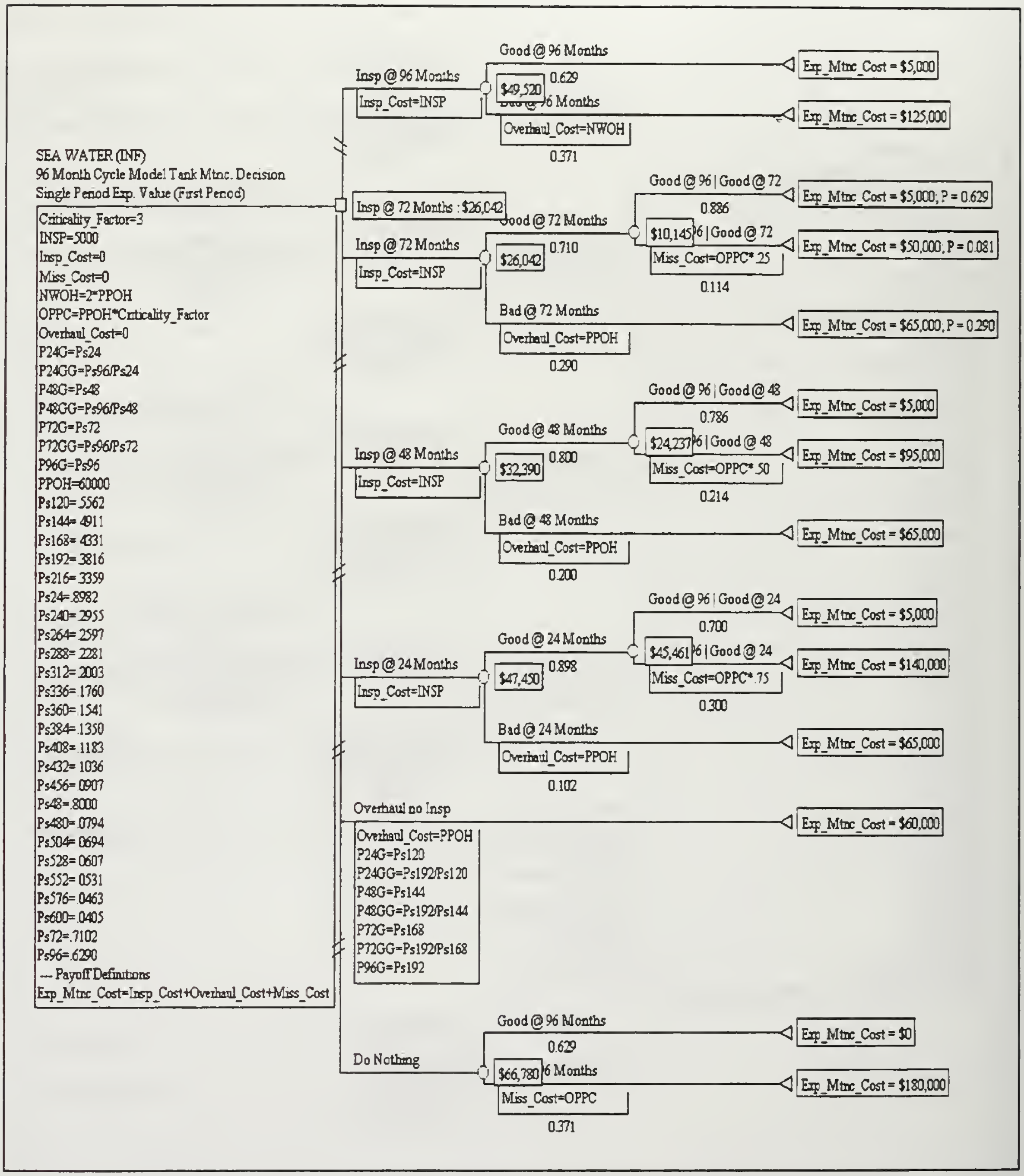


Figure I-8 Roll-back of SEA WTR (INF) Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

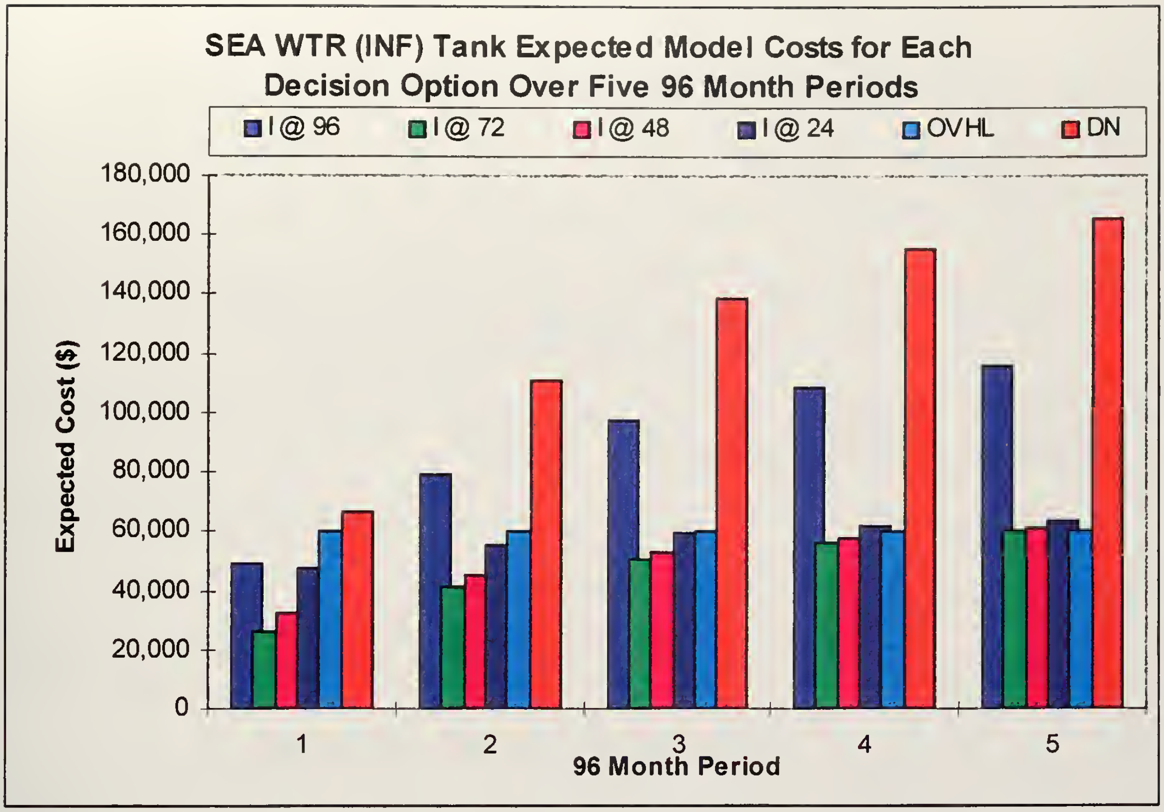


Figure I-9 Expected Model costs for various SEA WTR (INF) Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX J. CAT WING VOID GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for CAT WING VOID Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY CAT WING VOID GROUP, CVN 69					
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**COH '86 (99 MOS)**	**COH '95 (117 MOS)**	**COH '95 (216 MOS)**
CAT WING VOID	232	IOH:	0	0	0
		ICO:	0	0	0
		NICO:	0	0	0
% FAIL			0	0	0
CUM % FAIL			0	0	0
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				0	0
# FAILED				0	0
% (OF INSPECTED) FAILED				0	0
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure J-1 Summary of CAT WING VOID Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY CAT WING VOID GROUP, CVN 71					
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**SRA '89** (34 MOS)	**SRA '91** (61 MOS)	**SRA '95** (112 MOS)
CAT WING VOID	232	IOH	0	0	0
		ICO	0	0	0
		NICO	0	0	0
% FAIL			0	0	0
CUM % FAIL			0	0	0
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			0	0	0
# FAILED			0	0	0
			0	0	0
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure J-2 Summary of CAT WING VOID Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

CAT WING VOID GROUP, CVN 72			
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**EDSRA '96** (75 MOS)
CAT WING VOID	232	IOH	0
		ICO	0
		NICO	0
% FAIL			0
CUM % FAIL			0
TANK COATING FAILURE SUMMARY			
COATING AGE (MONTHS)			~75
# INSPECTED			0
# FAILED			0
% (OF INSPECTED) FAILED			0
INSPECTION CODE KEY			
IOH	= INSPECTED AND OVERHAULED		
ICO	= INSPECTED AND NOT OVERHAULED		
NICO	= NOT INSPECTED AND NOT OVERHAULED		

Figure J-3 Summary of CAT WING VOID Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).

APPENDIX K. CAT EXH GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for CATAPULT EXHAUST VOID Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY CAT EXHAUST GROUP, CVN 69					
DESIGNATION	# TANKS	INSPECTION CODE	COH '86 (99 MOS)	COH '95 (117 MOS)	COH '95 (216 MOS)
CATAPULT EXH	3	IOH:	1	0	0
		ICO:	2	0	0
		NICO:	0	1	2
% FAIL			33.33	0	0
CUM % FAIL			33.33	0	33.33
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				3	0
# FAILED				1	0
% (OF INSPECTED) FAILED				33.33	0
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure K-1 Summary of CAT EXH VOID Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
CAT EXHAUST GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
CATAPULT EXH	3	IOH	0	2	0
		ICO	0	1	0
		NICO	3	0	3
% FAIL			0.00	66.67	0.00
CUM % FAIL			0.00	66.67	66.67

TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~34	~61	~112
# INSPECTED	0	3	0
# FAILED	0	2	0
% (OF INSPECTED) FAILED	0.00	66.67	0.00

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure K-2 Summary of CAT EXH VOID Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
CAT WING VOID GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
CAT WING VOID	232	IOH	0
		ICO	0
		NICO	0
% FAIL			0
CUM % FAIL			0

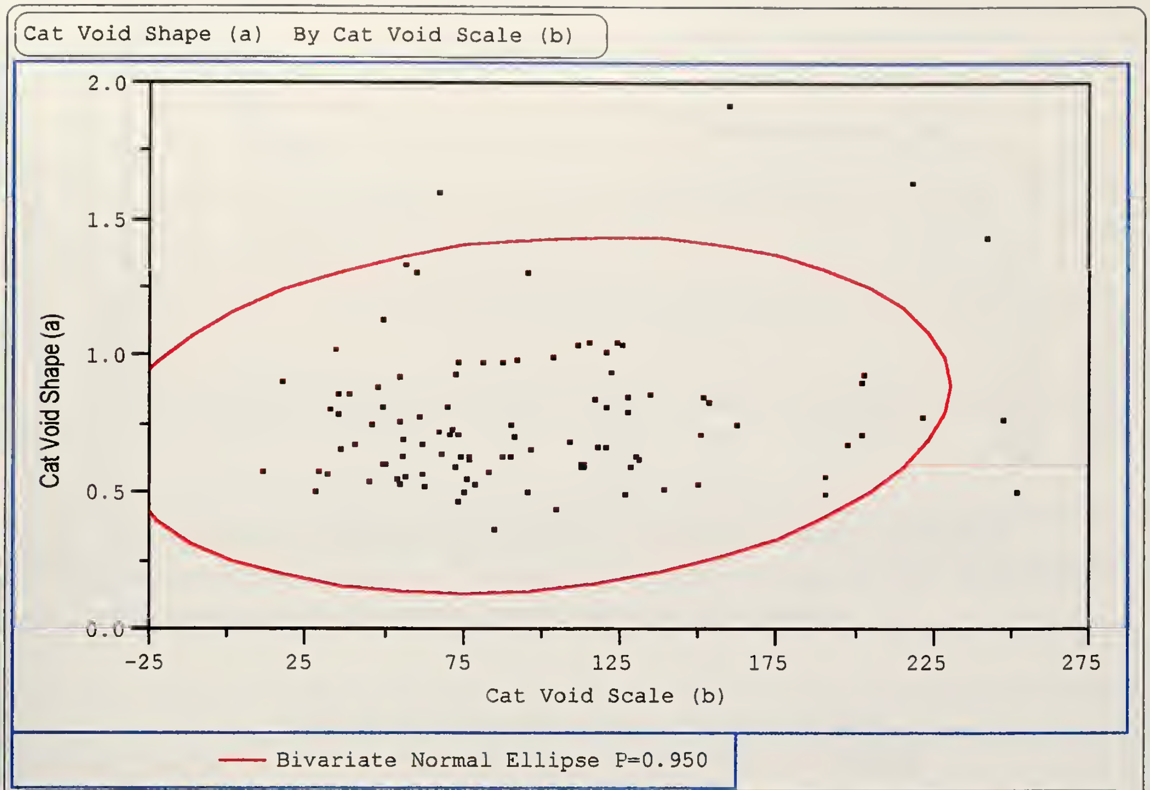
TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	0
# FAILED	0
% (OF INSPECTED) FAILED	0

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure K-3 Summary of CAT EXH VOID Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
Cat Void Scale (b)	97.44939	54.76717	0.173824	0.0837	100
Cat Void Shape (a)	0.794159	0.267866			

Figure K-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the CAT EXH VOID group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

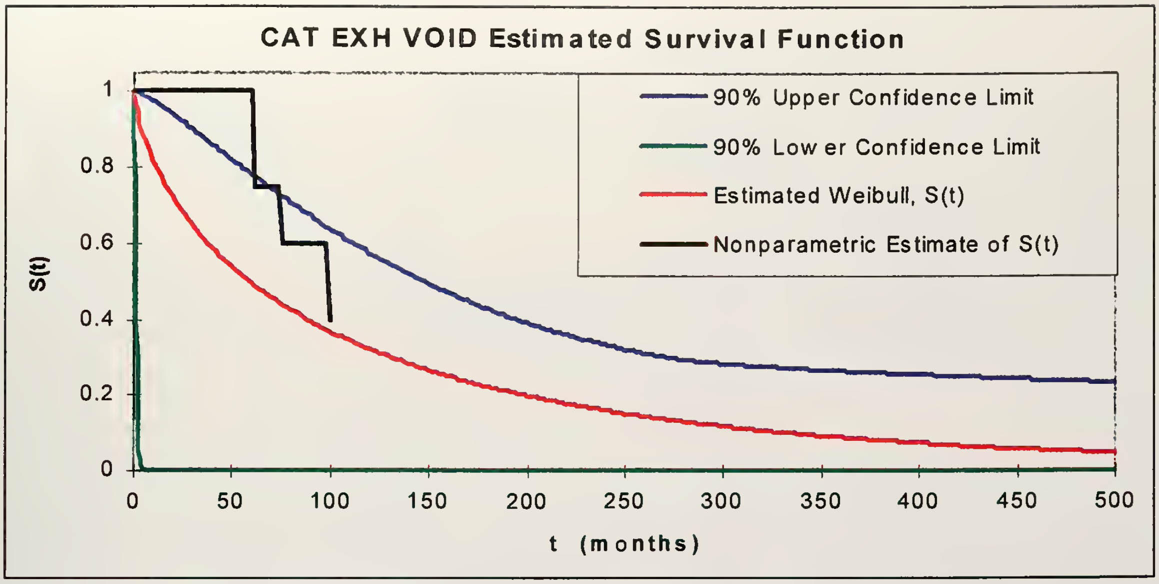


Figure K-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for CAT EXH VOID Group tanks compared to the nonparametric survival distribution.

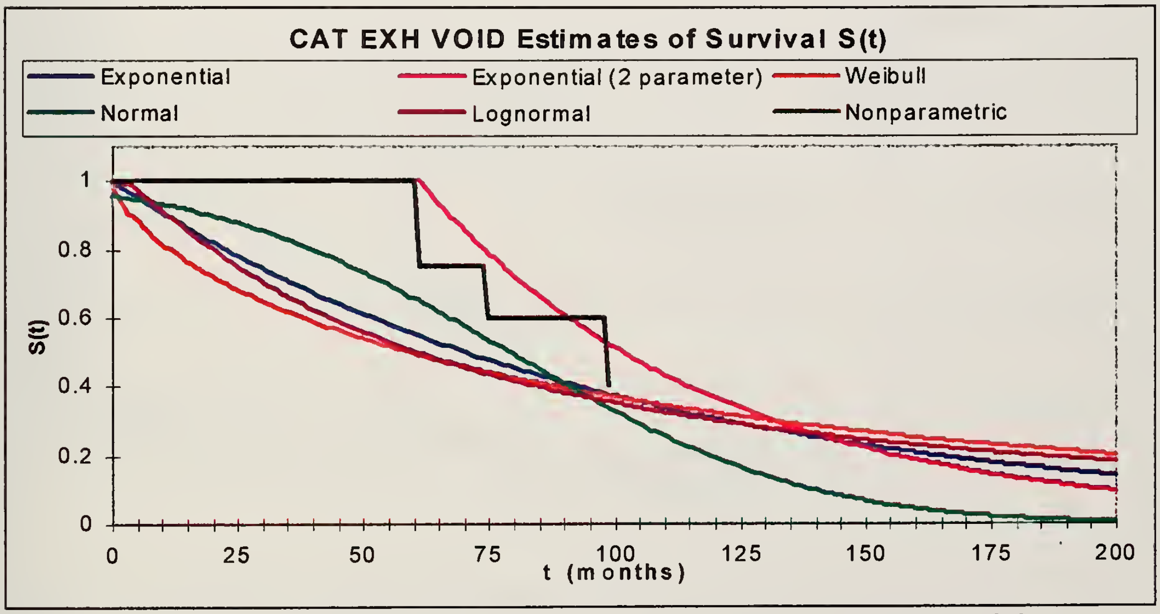


Figure K-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for CAT EXH VOID Group tanks.

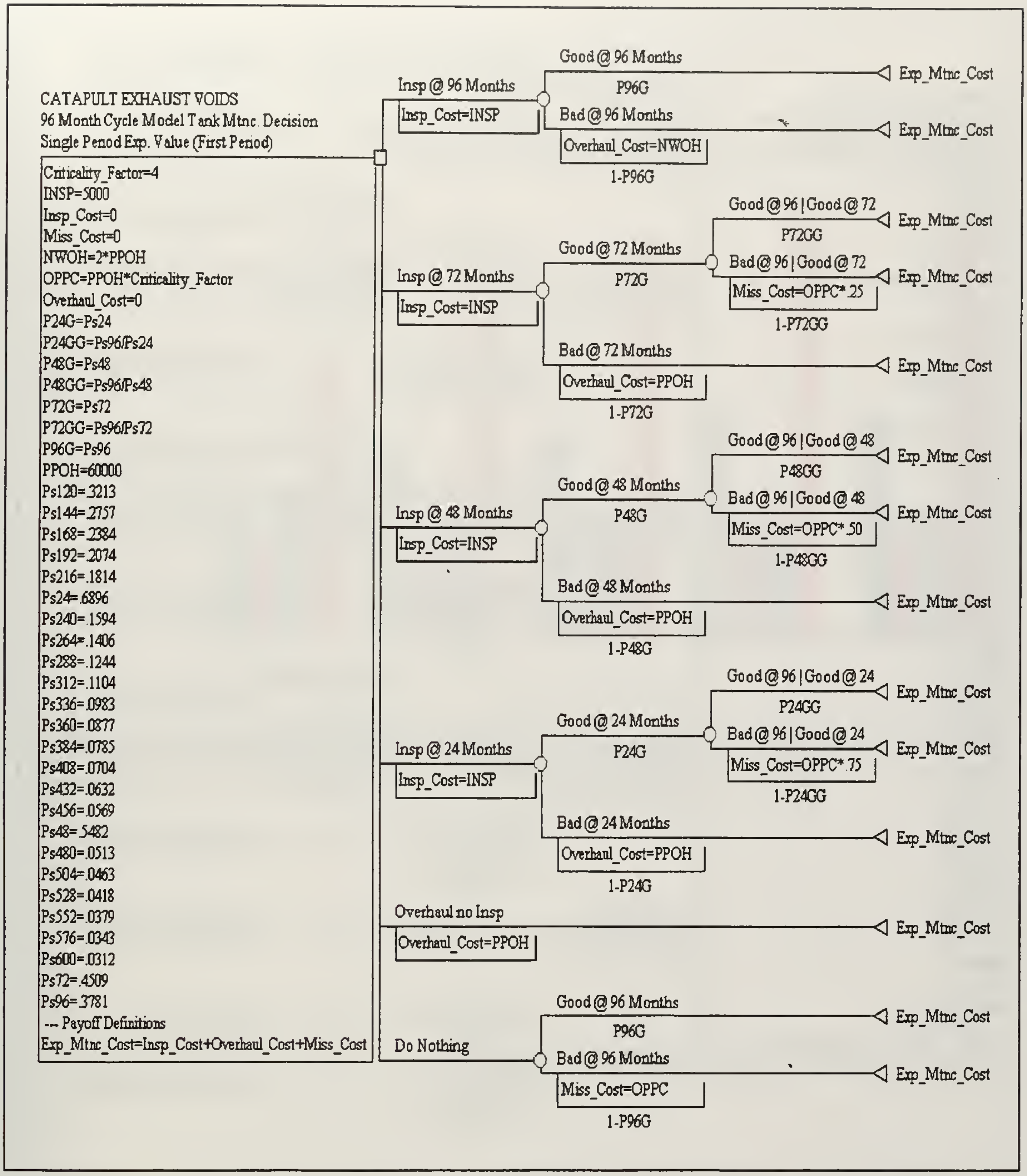


Figure K-7 96 month CAT EXH VOID Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

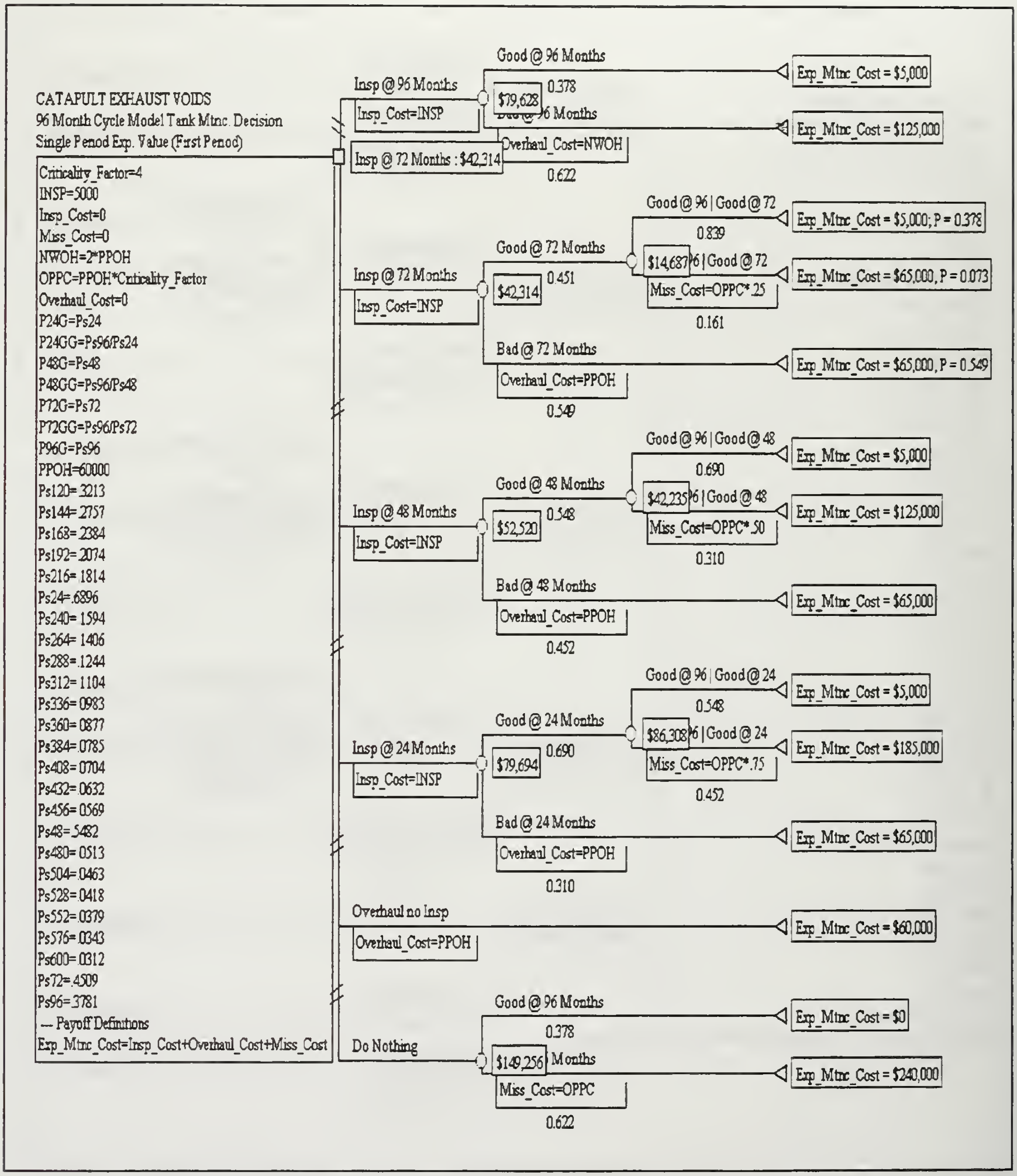


Figure K-8 Roll-back of CAT EXH VOID Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

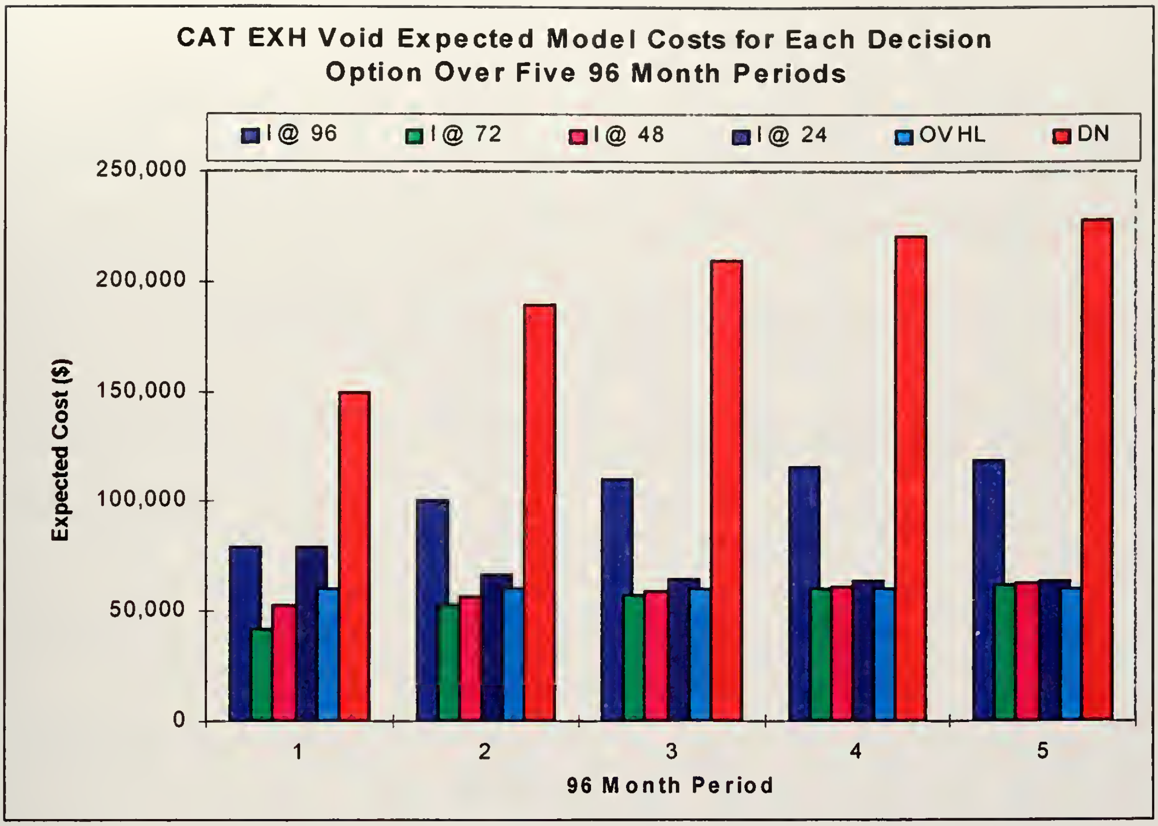


Figure K-9 Expected Model costs for various CAT EXH VOID Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX L. DRY GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for DRY Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

TANK COATING INSPECTION SUMMARY DRY GROUP, CVN 69					
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**COH '86 (99 MOS)**	**COH '95 (117 MOS)**	**COH '95 (216 MOS)**
COFFERDAMS	32	IOH:	9	0	4
		ICO:	20	9	16
		NICO:	3	0	3
VOIDS	218	IOH:	13	2	16
		ICO:	65	3	45
		NICO:	140	8	143
COMBINED	250	IOH:	22	2	20
		ICO:	85	12	61
		NICO:	143	8	146
% FAIL			20.56	14.29	24.69
CUM % FAIL			20.56	14.29	40.18
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)				~105	~210
# INSPECTED				38	20
# FAILED				9	4
% (OF INSPECTED) FAILED				23.68	20.00
INSPECTION CODE KEY					
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure L-1 Summary of DRY Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
DRY GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
COFFERDAMS	33	IOH	0	0	0
		ICO	0	0	0
		NICO	33	33	33
VOIDS	220	IOH	0	1	8
		ICO	6	14	18
		NICO	214	205	194
COMBINED	253	IOH	0	1	8
		ICO	6	14	18
		NICO	247	238	227
% FAIL			0.00	6.67	30.77
CUM % FAIL			0.00	6.67	30.77
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			6	15	26
# FAILED			0	1	8
% (OF INSPECTED) FAILED			0.00	6.67	30.77

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure L-2 Summary of DRY Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
DRY GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
COFFERDAMS	34	IOH	0
		ICO	4
		NICO	30
VOIDS	218	IOH	5
		ICO	48
		NICO	165
COMBINED	252	IOH	5
		ICO	52
		NICO	195
% FAIL			8.77
CUM % FAIL			8.77

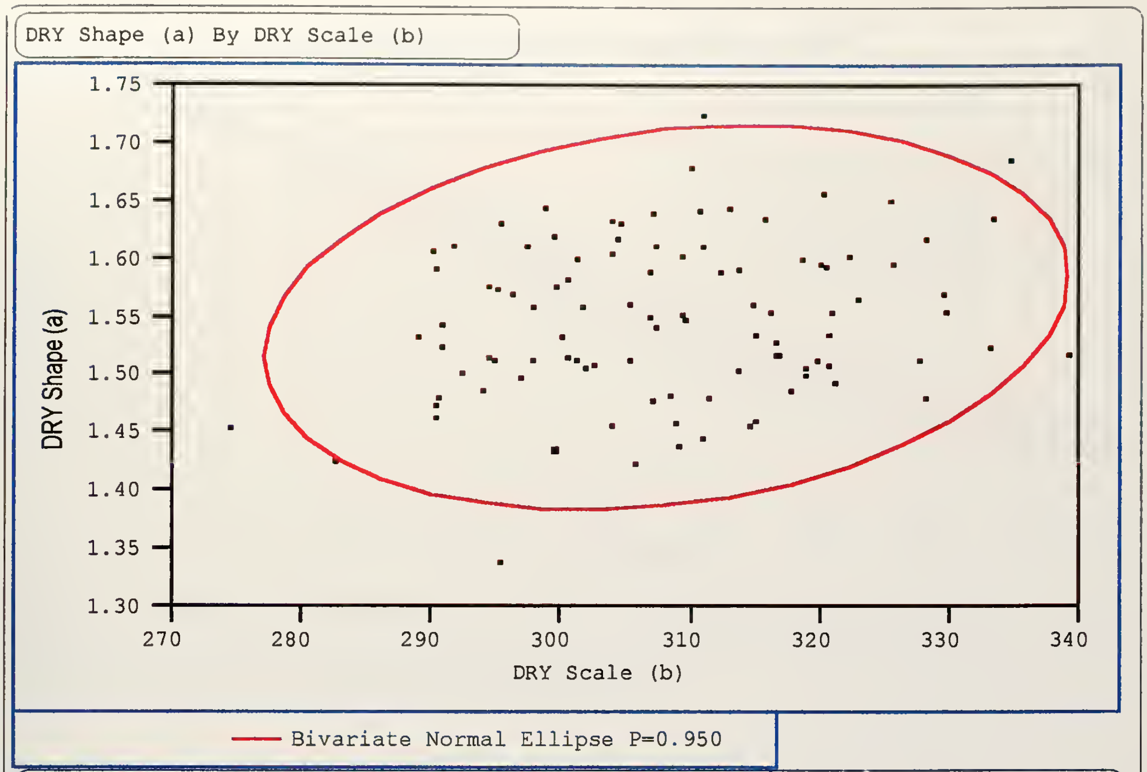
TANK COATING FAILURE SUMMARY

COATING AGE (MONTHS)	~75
# INSPECTED	57
# FAILED	5
% (OF INSPECTED) FAILED	8.77

INSPECTION CODE KEY

IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure L-3 Summary of DRY Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
DRY Scale (b)	308.2674	12.6839	0.213438	0.0330	100
DRY Shape (a)	1.550814	0.068053			

Figure L-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the DRY group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

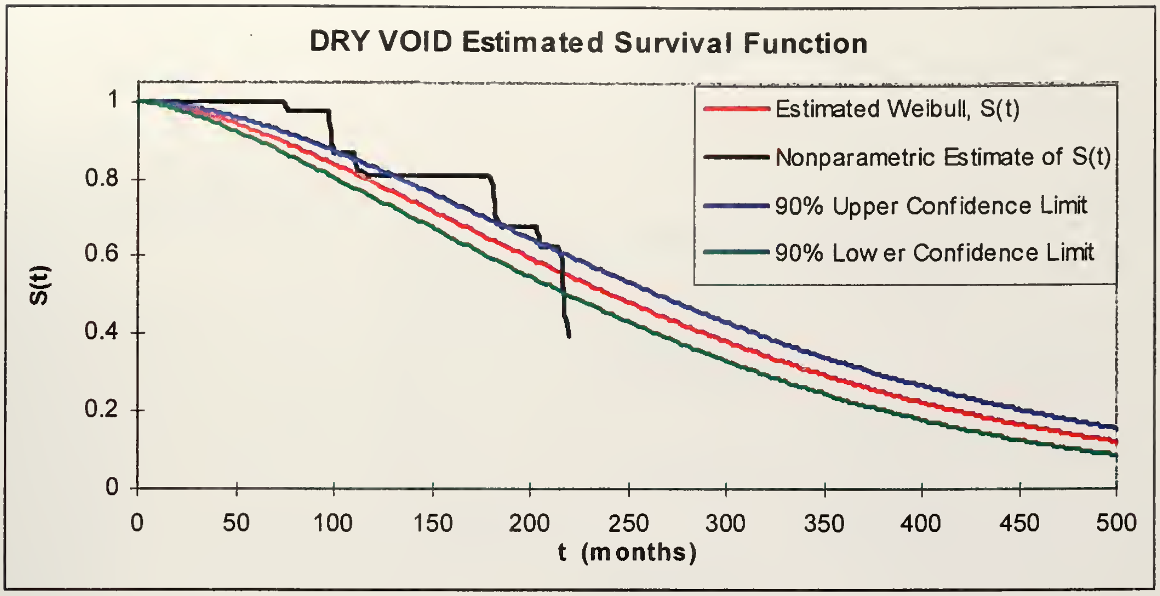


Figure L-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for DRY Group tanks compared to the nonparametric survival distribution.

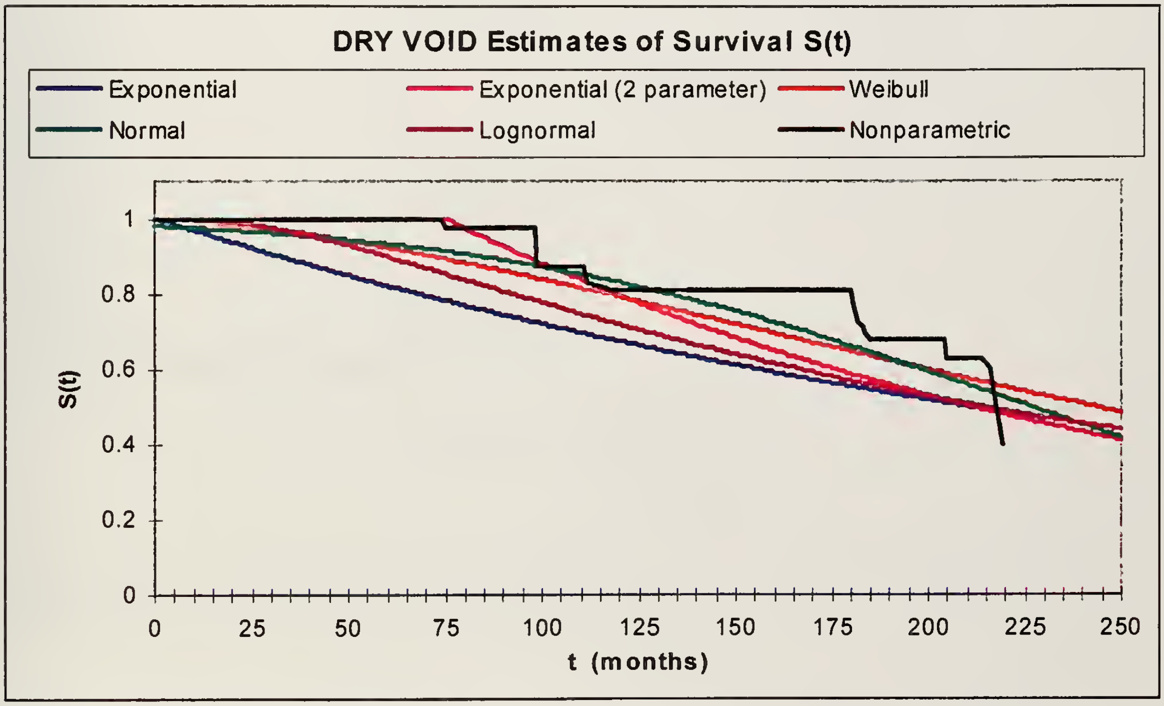


Figure L-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for DRY Group tanks.

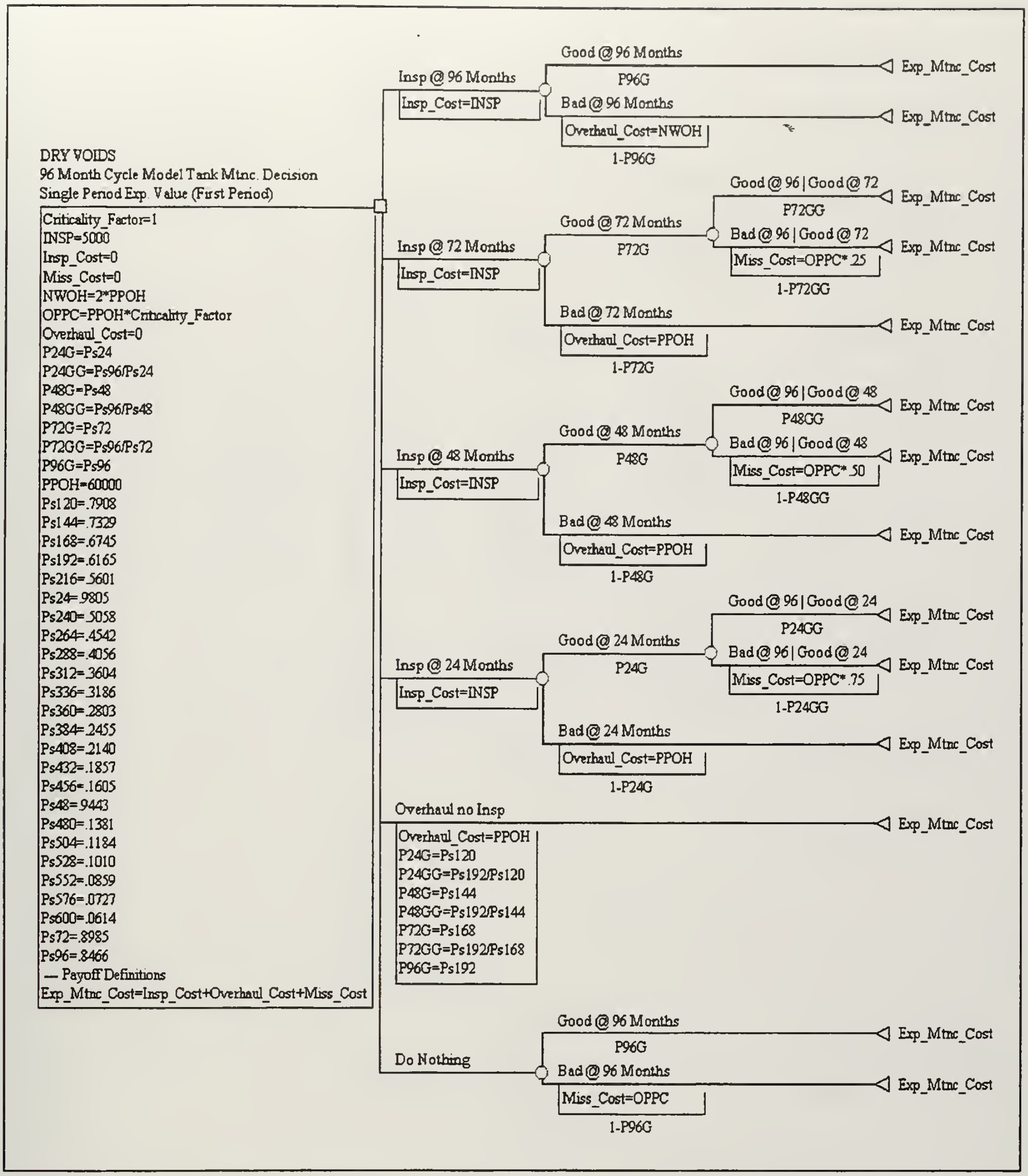


Figure L-7 96 month DRY Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

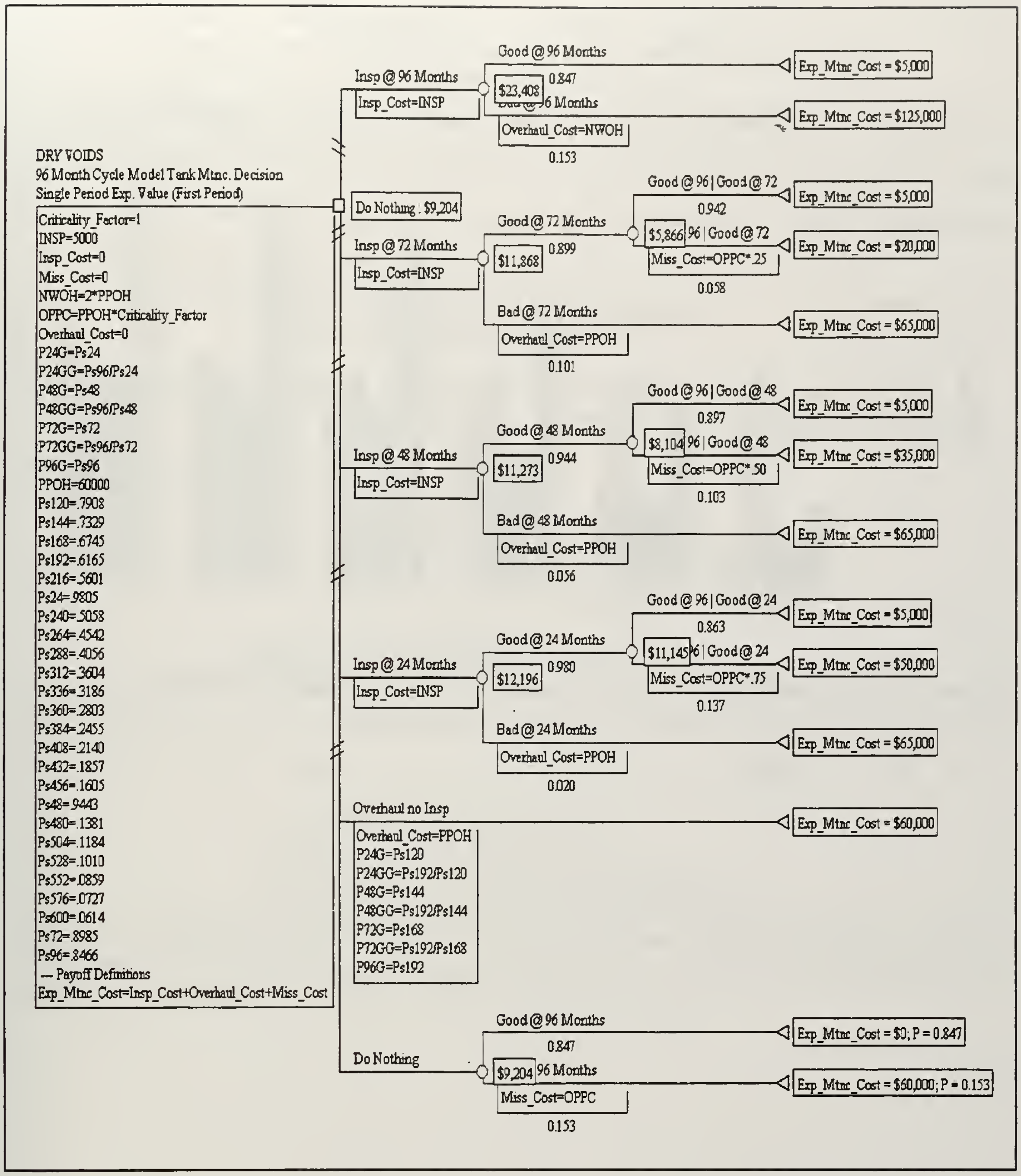


Figure L-8 Roll-back of DRY Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

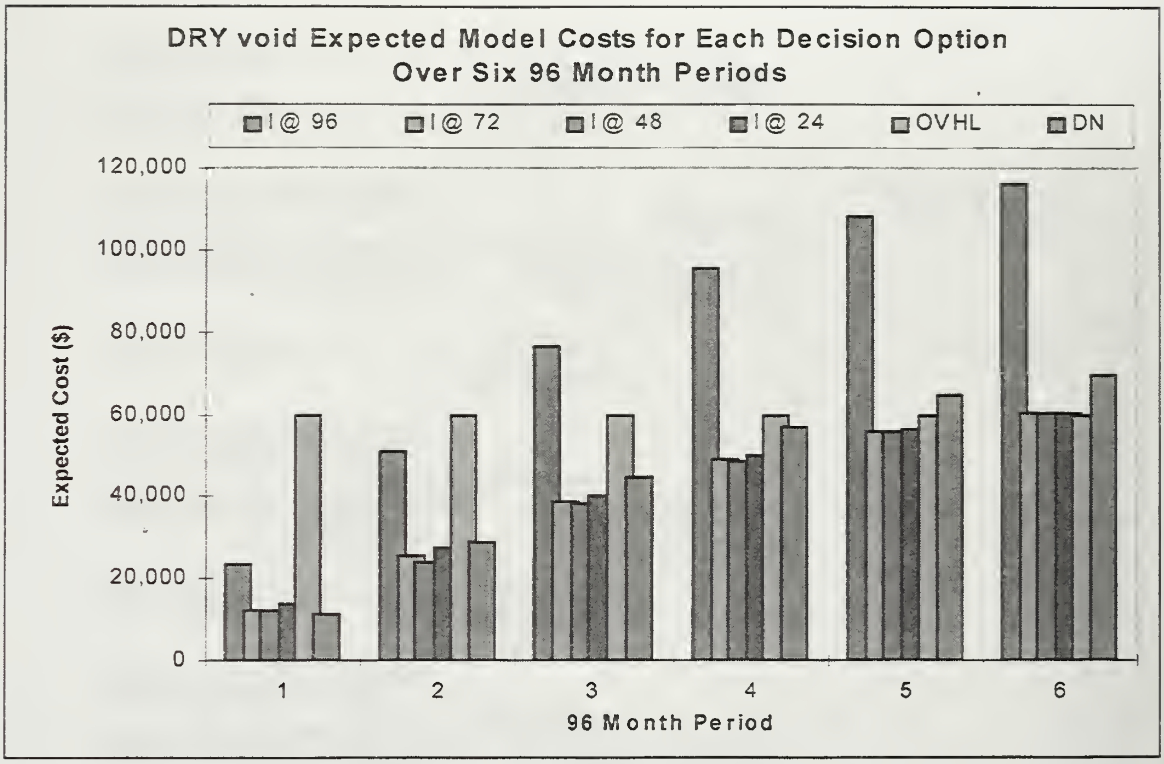


Figure L-9 Expected Model costs for various DRY Group tank inspection decision options over the first five 96 month periods of tank coating life.

APPENDIX M. SPONSON GROUP

This appendix provides a summary of the number of inspections, their times and the results of those inspections for SPONSON Group tanks on the CVN 69, CVN 71, and CVN 72. It also provides the plots that support the data analysis in Chapter V and figures that support the decision analysis of Chapter VI.

		TANK COATING INSPECTION SUMMARY SPON VOID GROUP, CVN 69			
DESIGNATION	**# TANKS**	**INSPECTION CODE**	**COH '86 (99 MOS)**	**COH '95 (117 MOS)**	**COH '95 (216 MOS)**
SPONSON VOID	7	IOH:	1	1	4
		ICO:	0	0	1
		NICO:	6	0	1
% FAIL			100.00	100.00	80.00
CUM % FAIL			100.00	100.00	100.00
		TANK COATING FAILURE SUMMARY			
COATING AGE (MONTHS)				~105	~210
# INSPECTED				2	5
# FAILED				2	4
% (OF INSPECTED) FAILED				100.00	80.00
		INSPECTION CODE KEY			
IOH	= INSPECTED AND OVERHAULED				
ICO	= INSPECTED AND NOT OVERHAULED				
NICO	= NOT INSPECTED AND NOT OVERHAULED				

Figure M-1 Summary of SPONSON Group tank inspections onboard CVN 69 recorded from Complex Overhaul (COH) periods in 1986 and 1995. Note that tanks overhauled in 1986 have younger lives than those not yet overhauled in 1995.

TANK COATING INSPECTION SUMMARY
SPONSON VOID GROUP, CVN 71

DESIGNATION	# TANKS	INSPECTION CODE	SRA '89 (34 MOS)	SRA '91 (61 MOS)	SRA '95 (112 MOS)
SPONSON VOID	8	IOH	0	0	0
		ICO	0	1	0
		NICO	8	7	8
% FAIL			0	0	0
CUM % FAIL			0	0	0
TANK COATING FAILURE SUMMARY					
COATING AGE (MONTHS)			~34	~61	~112
# INSPECTED			0	1	0
# FAILED			0	0	0
% (OF INSPECTED) FAILED			0	0	0

INSPECTION CODE KEY
IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

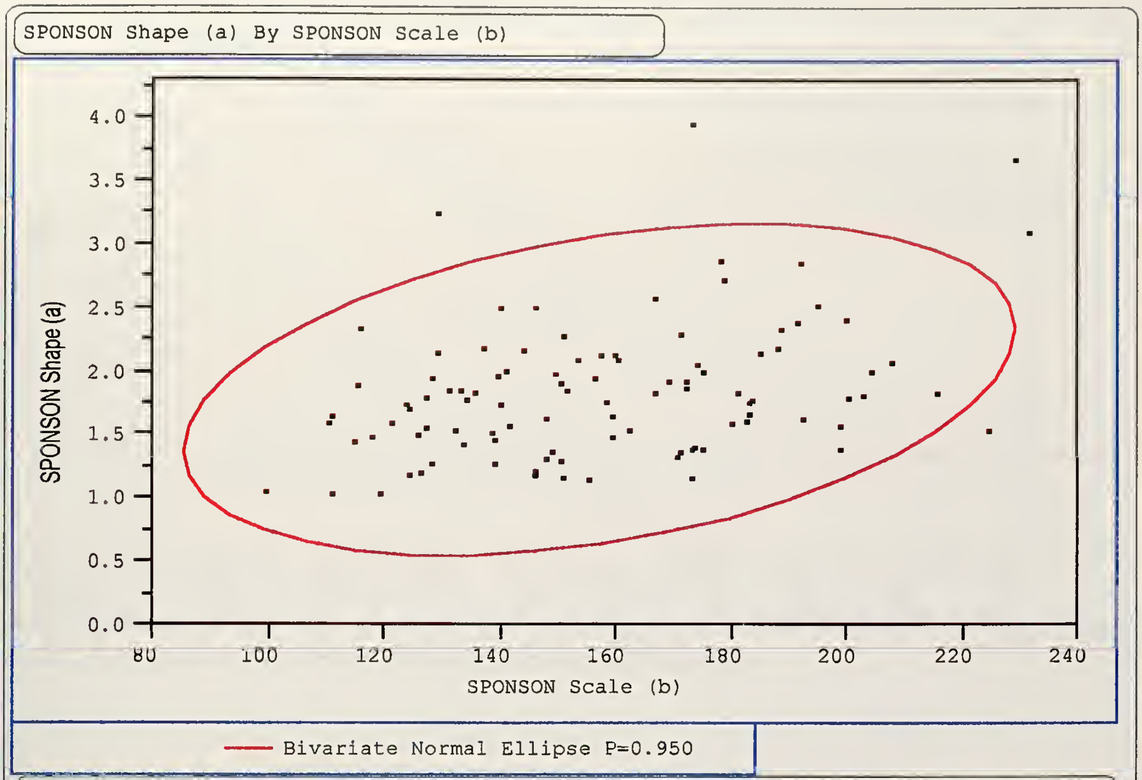
Figure M-2 Summary of SPONSON Group tank inspections onboard CVN 71 recorded from Selective Restricted Availability (SRA) periods in 1989, 1991, and 1995.

TANK COATING INSPECTION SUMMARY
SPONSON VOID GROUP, CVN 72

DESIGNATION	# TANKS	INSPECTION CODE	EDSRA '96 (75 MOS)
SPONSON VOID	7	IOH	0
		ICO	2
		NICO	5
% FAIL			0
CUM % FAIL			0
TANK COATING FAILURE SUMMARY			
COATING AGE (MONTHS)			~75
# INSPECTED			2
# FAILED			0
% (OF INSPECTED) FAILED			0

INSPECTION CODE KEY
IOH = INSPECTED AND OVERHAULED
ICO = INSPECTED AND NOT OVERHAULED
NICO = NOT INSPECTED AND NOT OVERHAULED

Figure M-3 Summary of SPONSON *Group tank inspections onboard CVN 72 recorded from 1996 Extended Dry-docking Selective Restricted Availability (EDSRA).*



Bivariate

Variable	Mean	Std Dev	Correlation	Signif. Prob	Number
SPONSON Scale (b)	157.65	29.34	0.37	0.0001	100
SPONSON Shape (a)	1.8786	0.538			

Figure M-4 Bootstrapped estimates and 95% confidence ellipse for Weibull parameters of Shape (α) and Scale (β) for the SPONSON group. (This figure is a screen capture from JMP version 3.1.6 by SAS Institute Inc.)

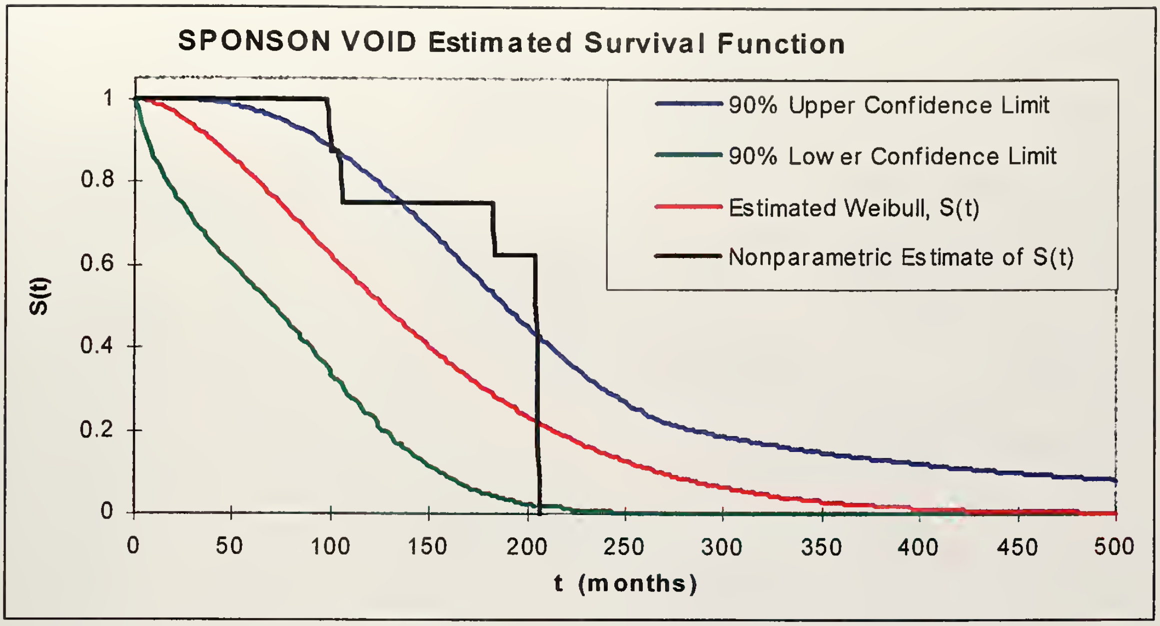


Figure M-5 Maximum Likelihood fit (with 90% confidence bounds) of Weibull distribution describing the survival function S(t) of tank coatings for SPONSON Group tanks compared to the nonparametric survival distribution.

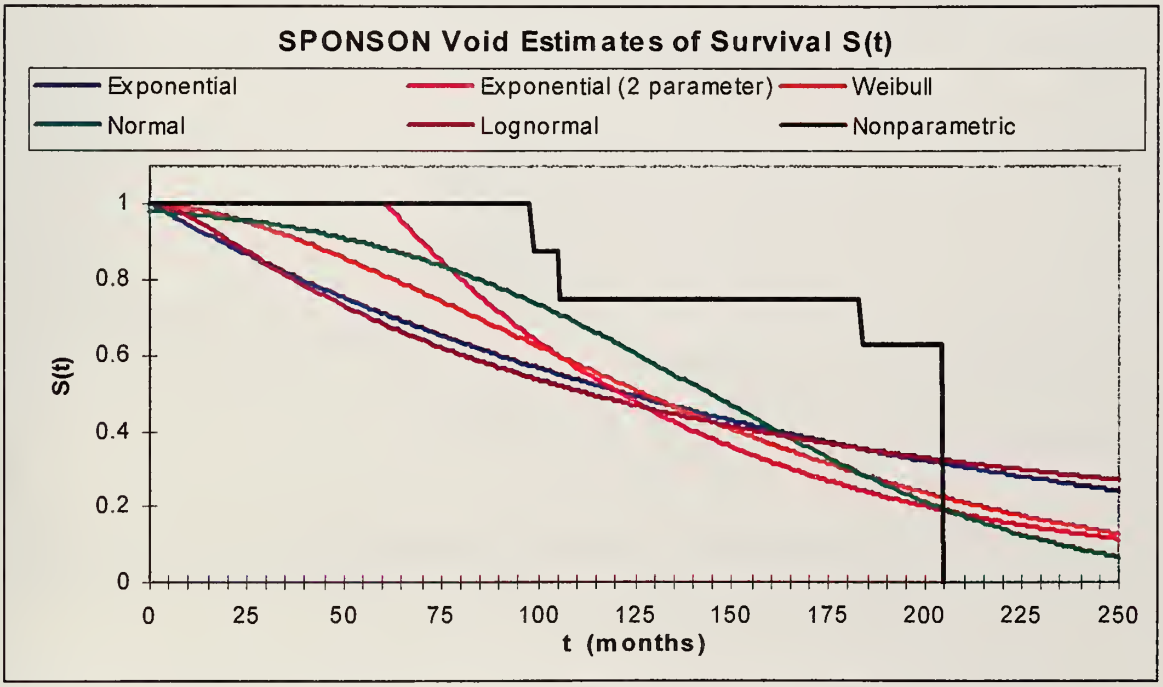


Figure M-6 Maximum Likelihood fits of parametric and nonparametric candidate distributions describing the survival function S(t) of tank coatings for SPONSON Group tanks.

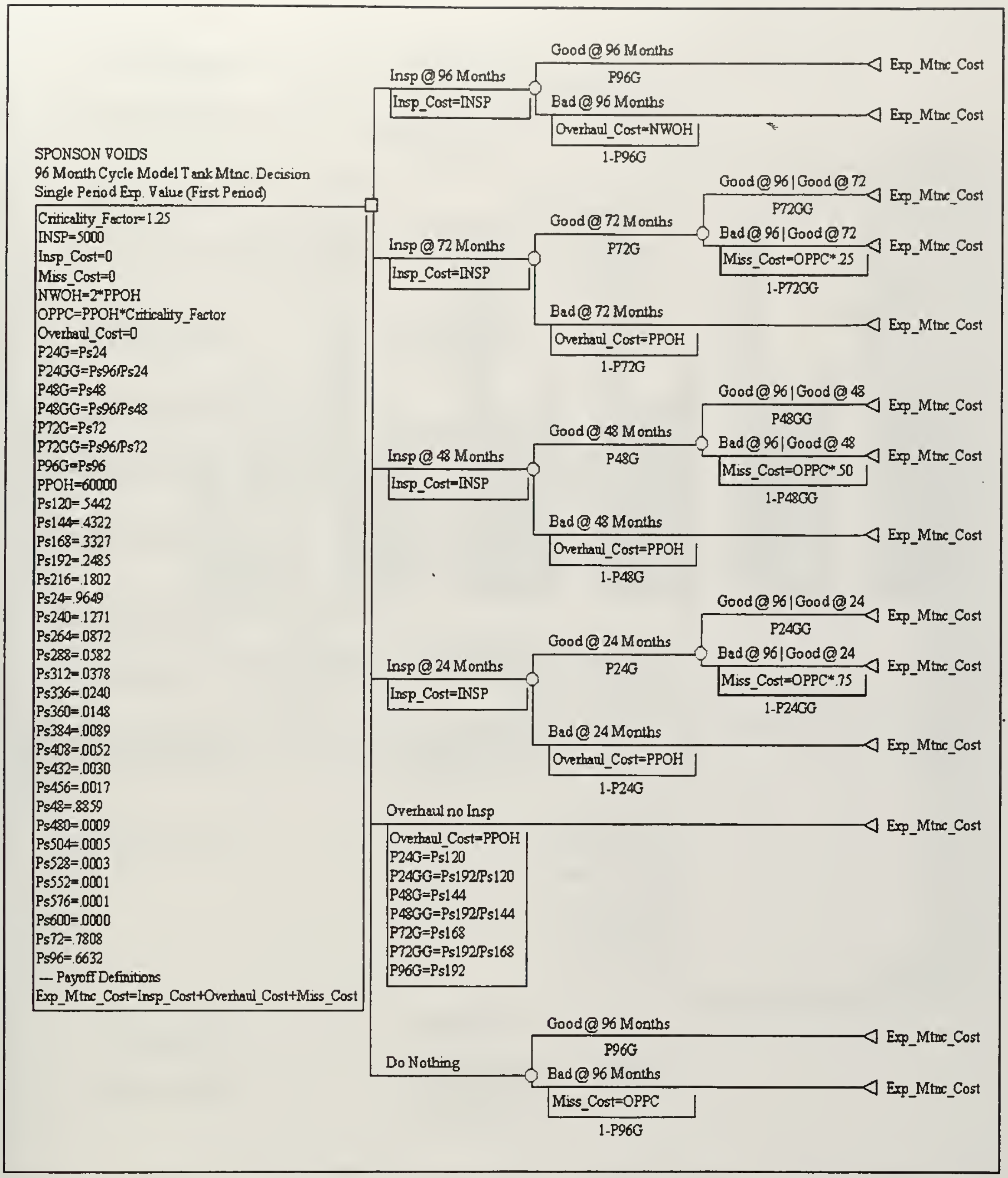


Figure M-7 96 month SPONSON Group Tank Inspection Decision Model. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

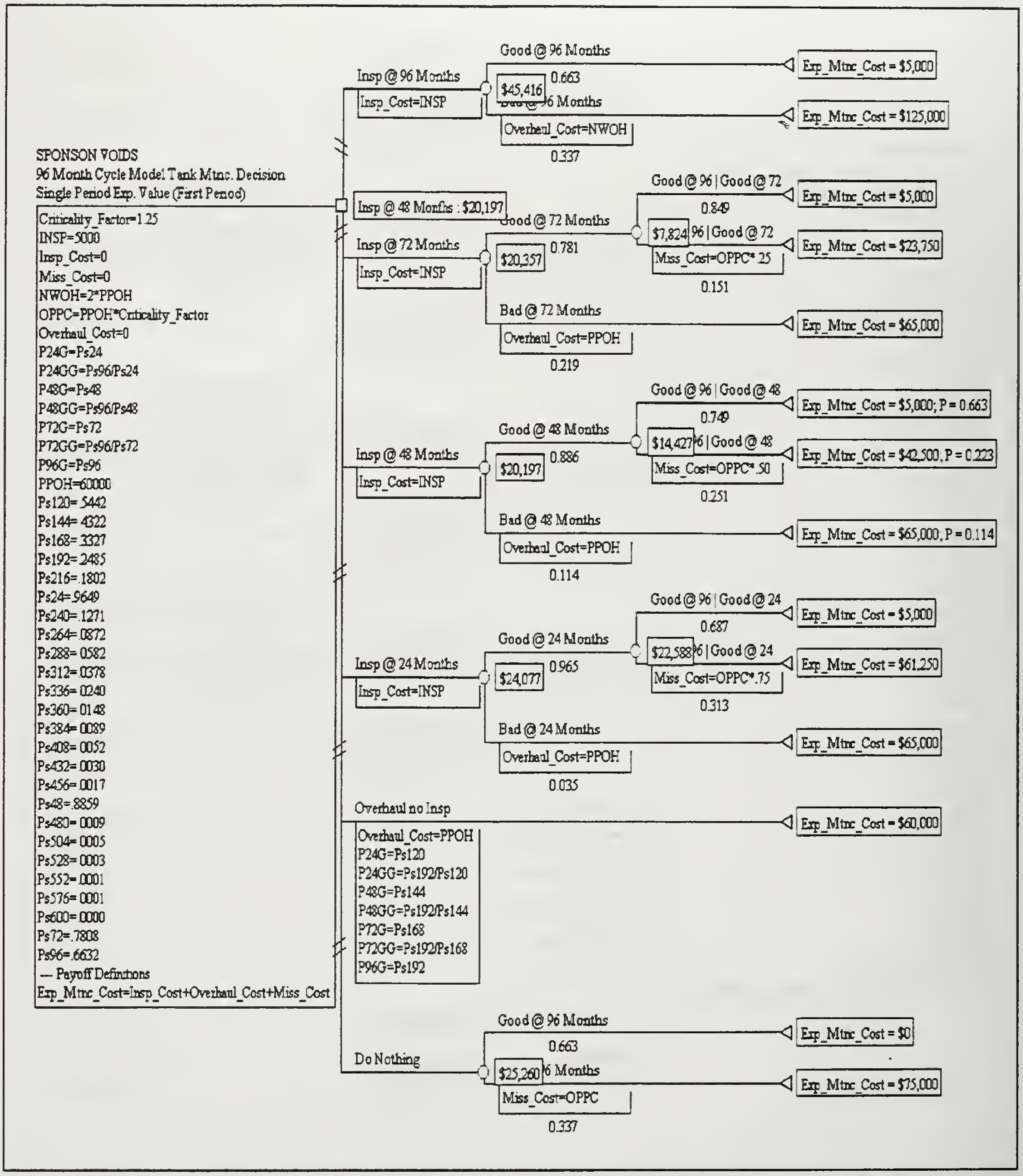


Figure M-8 Roll-back of SPONSON Group Tank Inspection Decision Model showing expected costs and recommended action to take during the first 96 month period of tank coating life. (This figure is a screen capture from DATA version 2.6.4 by TreAge Software Inc.)

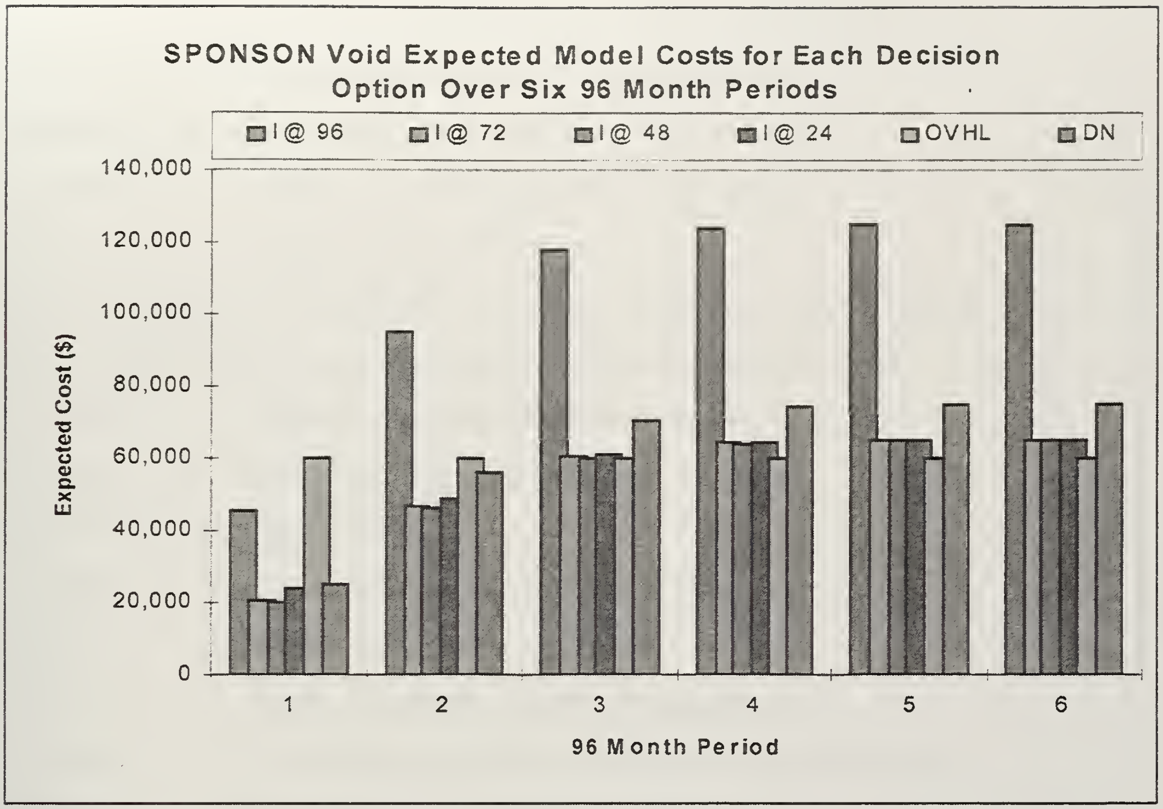


Figure M-9 Expected Model costs for various SPONSON Group tank inspection decision options over the first five 96 month periods of tank coating life.

LIST OF ACRONYMS AND ABBREVIATIONS

"AIRLANT"	Commander Naval Air Forces Atlantic Fleet
"AIRPAC"	Commander Naval Air Forces Pacific Fleet
"AMSEC"	American Systems Engineering Corporation
"ATS"	Applied Technical Systems
"CAT EXH VOID"	Tanks that provide quench volume for Catapult brakes
"CAT WING VOID"	Tanks that provide drainage for Catapult tracks
"CEMAT"	Carrier Engineering Maintenance Assist Team
"CLER"	Carrier Life Extending Repairs
"COH"	Complex Overhaul
"CSMP"	Consolidated Ship's Maintenance Plan
"CVN __"	Aircraft Carrier Nuclear Powered
"DRY"	Tanks not normally utilized for liquid storage
"EDSRA"	Extended Dry-docking Selected Restricted Availability
"HM&E"	Housekeeping and Maintenance Engineering
"IMA"	Intermediate Maintenance Activity
"JP-SERV"	Tanks characterized as Service tanks for JP-5 Fuel
"J(TRANS)"	Tanks characterized as Transient Storage for JP-5 Fuel
"J(FULL)"	Tanks characterized as Static Storage for JP-5 Fuel
"LAN"	Local Area Network
"LUBE OIL"	Tanks characterized as Bulk Lubricating Oil Storage
"MRC"	Maintenance Requirements Cards
"PERA(CV)"	Planning and Engineering for Repairs and Alterations for Aircraft Carriers
"PMS"	Preventive Maintenance System
"PO"	Petty Officer
"SEA WTR (FREQ)"	Tanks Frequently exposed to Sea Water
"SEA WTR (INF)"	Tanks Infrequently exposed to Sea Water
"SPONSON"	Tanks formed by fairing of the ships outer hull surface

"SRA"	Selected Restricted Availability
"TLI"	Tank Level Indicator
"T&VDB"	Data Base of Tank and Void inspection records
"WCS"	Work Center Supervisor

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